LBNE Near Detector Workshop

T2K Oscillation Measurements

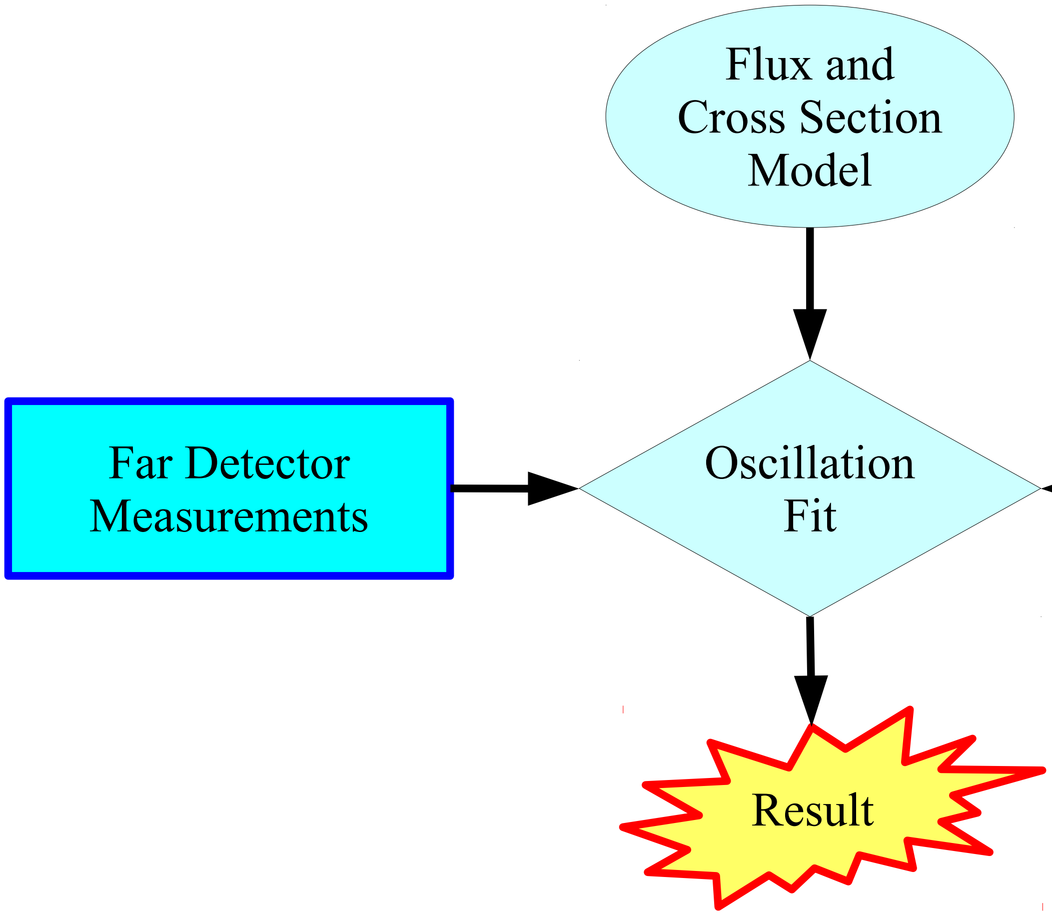
or

How the T2K Oscillation Analysis uses the ND280 Detectors

Clark McGrew
Stony Brook Univ.
for T2K

- Introduction: Managing Systematic Errors
  - Detector Systematics
  - Model Systematics
- The T2K Experiment
  - Far Detector Measurements
  - Near Detector Measurements
- Using the Near Detector
- Effect on the Oscillation Analysis

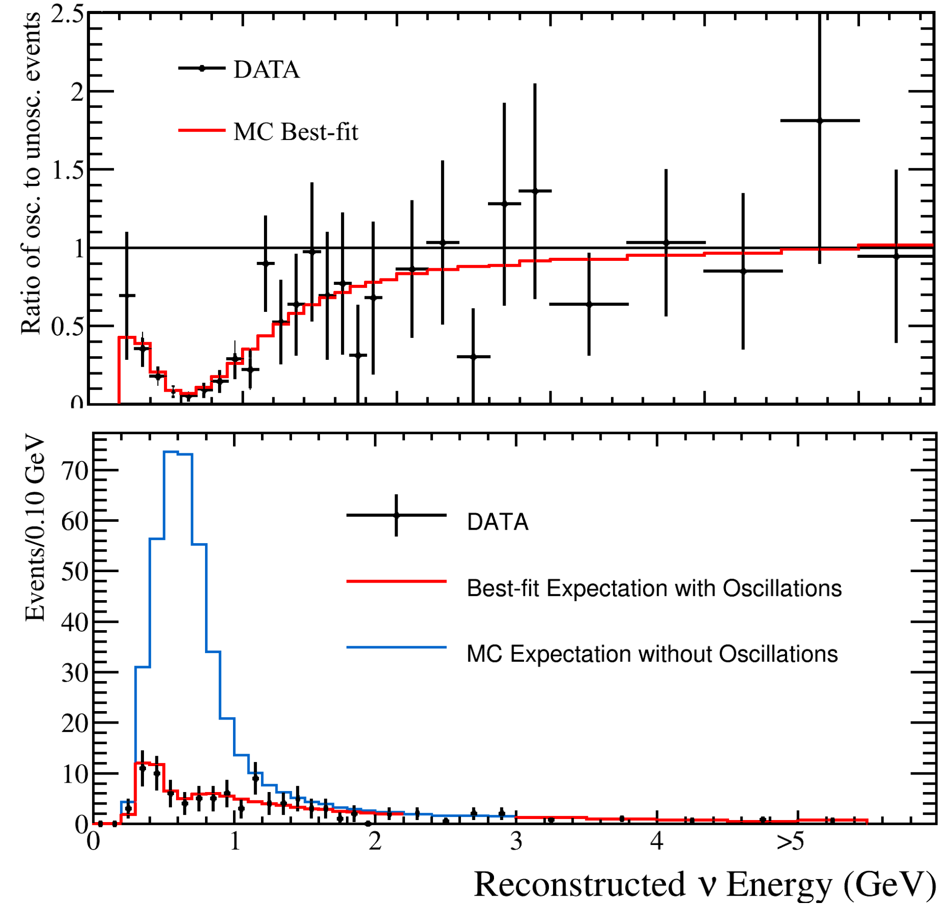
Conceptual Map of a Generic Oscillation Analysis



Oscillations and Neutrinos

Case Study: T2K ν_μ Disappearance

- Ability to reconstruct neutrino energy directly impacts the ability to determine oscillation parameters.
  - This is generically true, even if you don't explicitly reconstruct the neutrino energy.
  - The shape of the neutrino energy resolution has a strong effect
    - Tails affect the ability to measure the mixing parameters.
- Because of the oscillations, the near and far spectra are very different.
  - For precision measurements, we need to know how they are different (i.e. the effect of oscillations)



T2K 2013 disappearance result

The T2K ν_μ Energy Range

- Flux largely is below 1 GeV
  - Cross section dominated by CCQE
- Analyze using a charged current with no pion sample.
  - Sample defined by the observables, not the model
  - Contributions from several cross section channels
- Reconstruct neutrino assuming the target is a neutron
  - $\nu_\mu + n \rightarrow \mu^- + p$ (no pions)
    - Assume neutron is at rest
    - Reconstruct energy from μ^- kinematics
- Correct for assumptions using a neutrino cross section model

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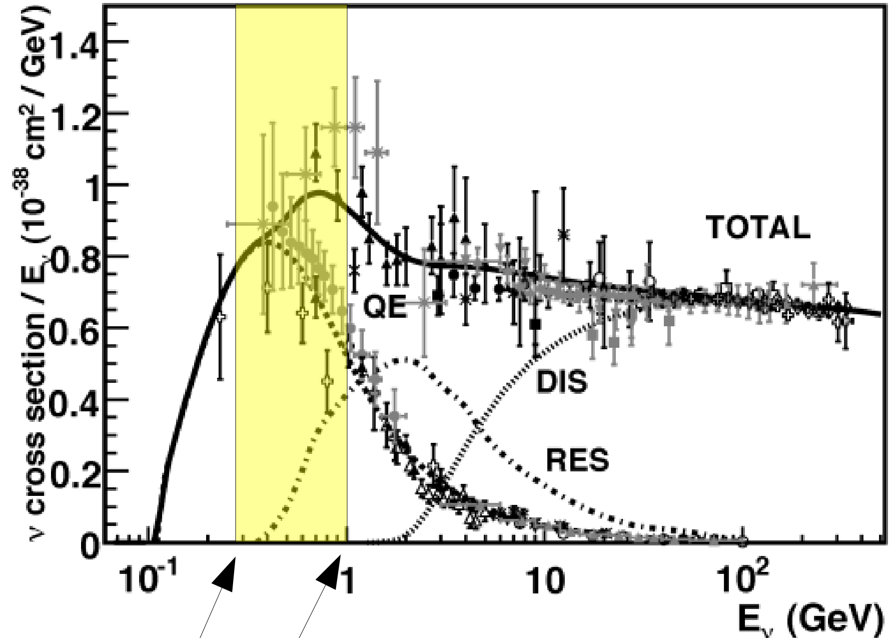
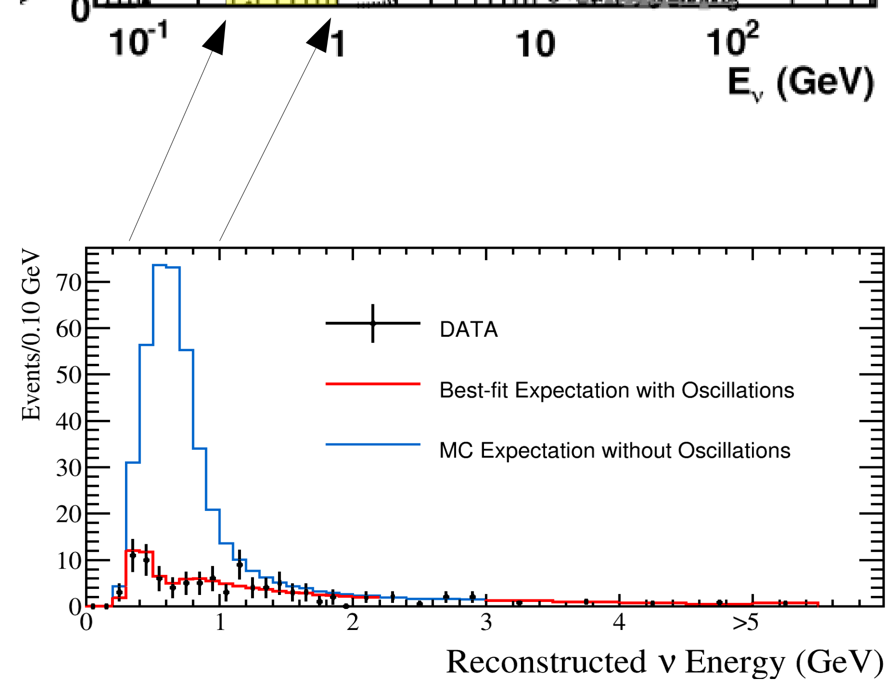
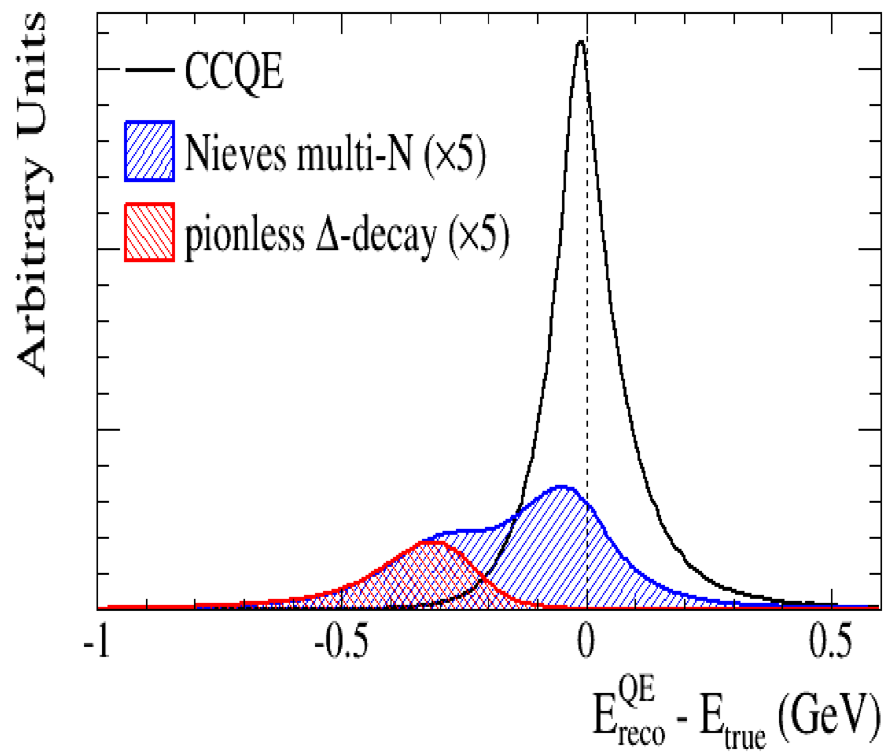




Complications...

a partial list

- Initial state of the target
  - Fermi Gas
  - Spectral Function
- Charged charged current quasi-elastic is not the only mode which will produced a single lepton with no pions
  - Resonant scattering with pion absorption
    - Pionless Δ – decay
  - Multi-nucleon effects
- Final state interactions
  - Charge exchange
  - Absorption
  - Rescattering

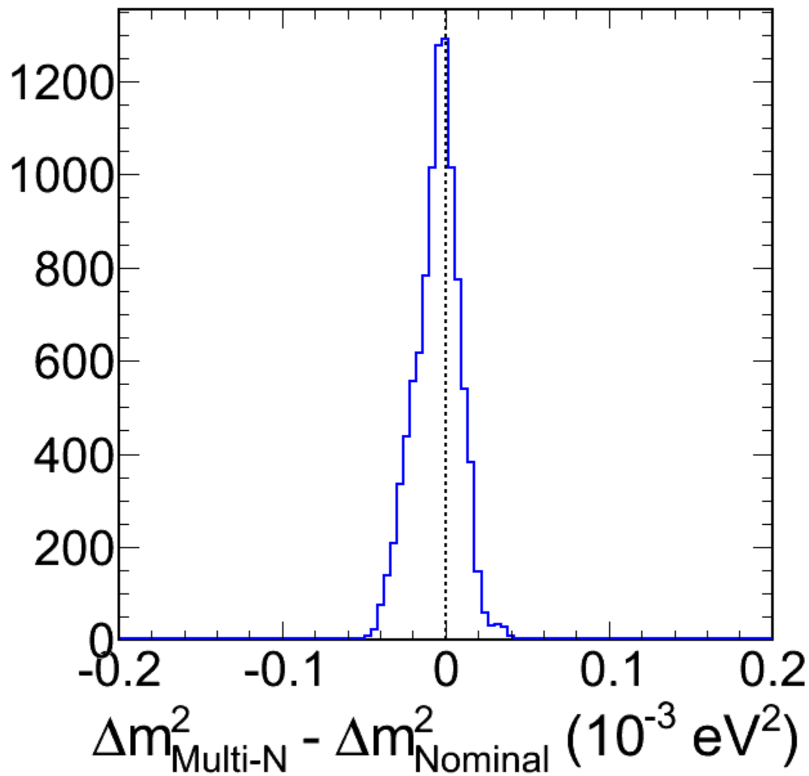


Examples of different models and the effect on the reconstructed energy.

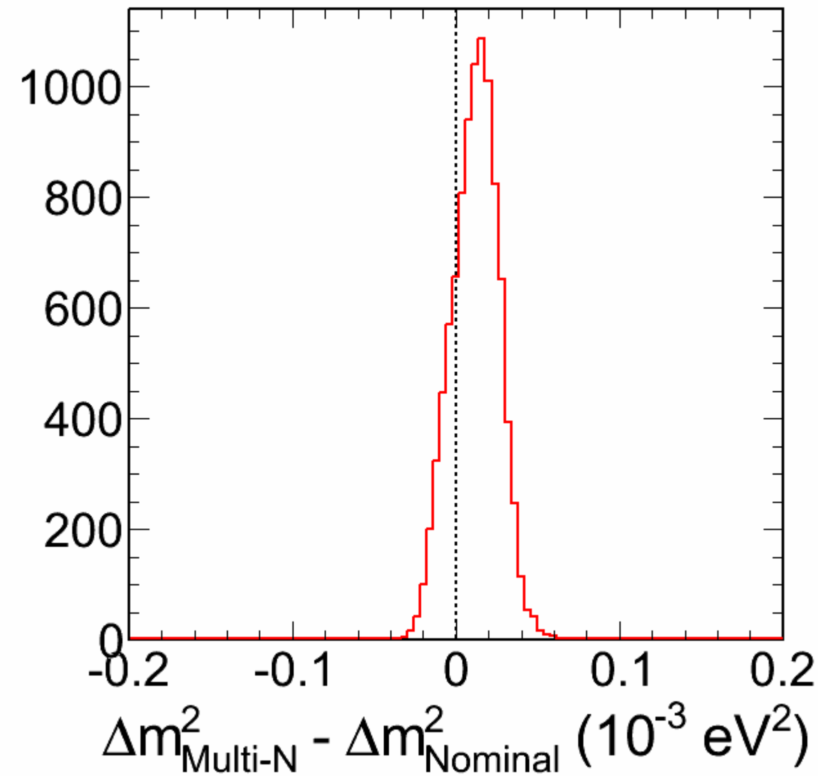
Bias introduced into the reconstructed neutrino energy.

Effect on Reconstructed Δm^2

- Interactions in the nucleus are complex with different models predicting different neutrino energy reconstruction
  - More neutrino interaction modeling is needed
  - More neutrino interaction measurements are needed to evaluate the models



Nieves 2p-2h model



Martini MEC model

Currently, this model uncertainty alone limits the T2K Δm^2 resolution to about 3%

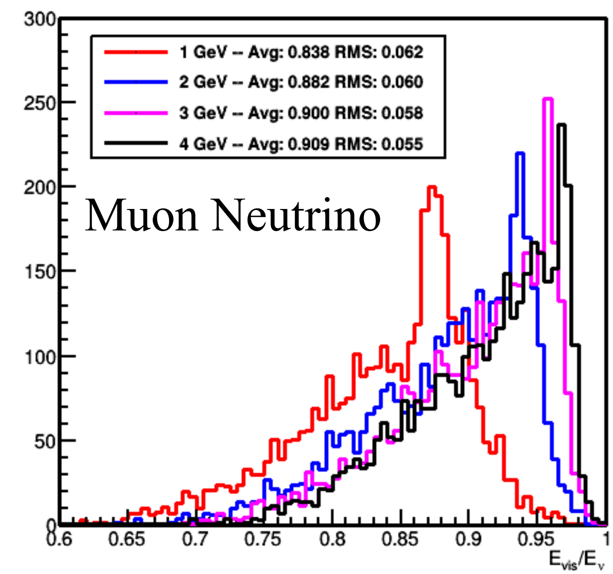
General Comment on Experiments

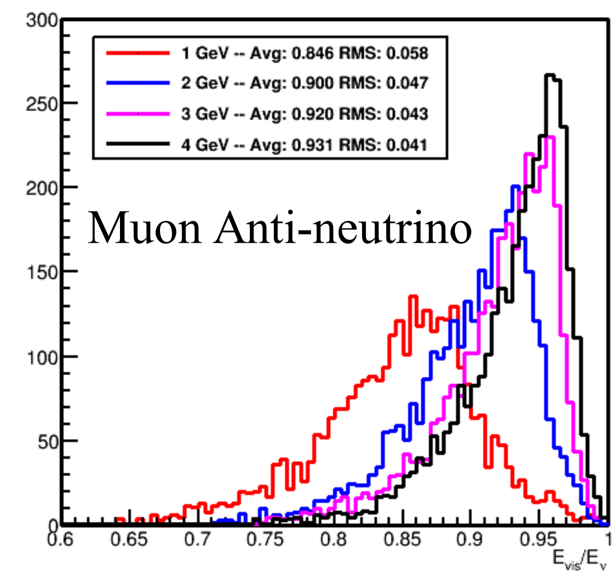
- Reconstructing the neutrino energy requires an interaction model
  - We (usually) don't know the target kinematics.
  - We (often) don't see all of the products.
- Sometimes, even when we have a model, there isn't enough information to fully reconstruct the neutrino energy.
  - The honest statement would be: “Usually, even when...”
- In general, neutrino energy isn't actually reconstructed
  - The final neutrino energy distributions are “unfolded” based on
    - Models of the neutrino interactions
    - Models of the detector performance
    - Models of expected flux

LAr is Not Immune...

a.k.a. an LBN(E) near detector sales pitch

- What's being shown:
  - The ratio of energy deposited as ionization to the neutrino energy
    - Assuming a perfect detector with
      - perfect drift corrections
      - perfect "Birk's Law" corrections
      - perfect muon id...
  - For
    - Mono-energetic CC muon neutrino interactions
    - Simulated using GENIE
    - Incident on an "infinite" LAr target
- Predicted energy response is "complicated"
  - The energy response varies as a function of neutrino energy
  - The shape of the response for neutrinos is different than for anti-neutrinos.
- Naively: The ν-Ar cross section will need to be understood in detail.





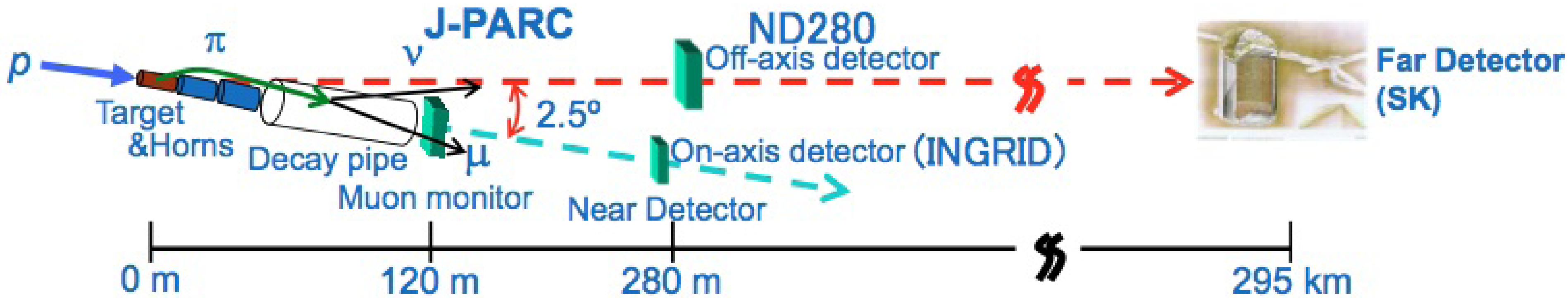
The T2K Experiment

(Tokai-to-Kamioka)

- Neutrino Oscillation Physics
  - Precision measurement of neutrino oscillation parameters: θ_{13}, θ_{23}, Δm^2_{31}, δ_{CP}
    - Observe both appearance and disappearance channels
      - $(\nu_\mu \to \nu_e)$, $(\nu_\mu \to \nu_\mu)$, $(\bar{\nu}_\mu \to \bar{\nu}_e)$, $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
- Neutrino Cross Physics
- T2K has currently received ~8% of expected exposure: early days...
  - Anti-neutrino data collected in May 2014

Reported neutrino exposure:
6.57×10^{20} protons on target

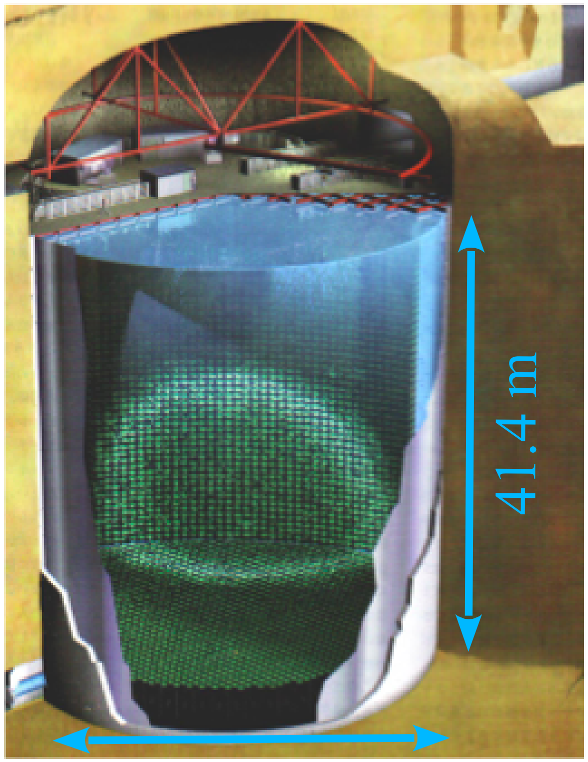
T2K Overview



- High Power Accelerator
  - 30 GeV proton beam on 90 cm graphite target
  - Pion production measured by CERN NA61
- Intense and High Quality Neutrino Beam
  - Three magnetic horns focus sign selected hadrons
- Secondary Beam Monitoring
  - Muon monitors behind beam dump: muon intensity and direction
- High Resolution Near Detector at 280 m
  - INGRID on-axis: ν beam direction and intensity
  - ND280 off-axis: cross sections, ν beam spectrum, flux and flavor
- Far Detector at 295 km @ 2.5 degree off-axis
  - Super-Kamiokande: measure ν flux, spectrum and flavor

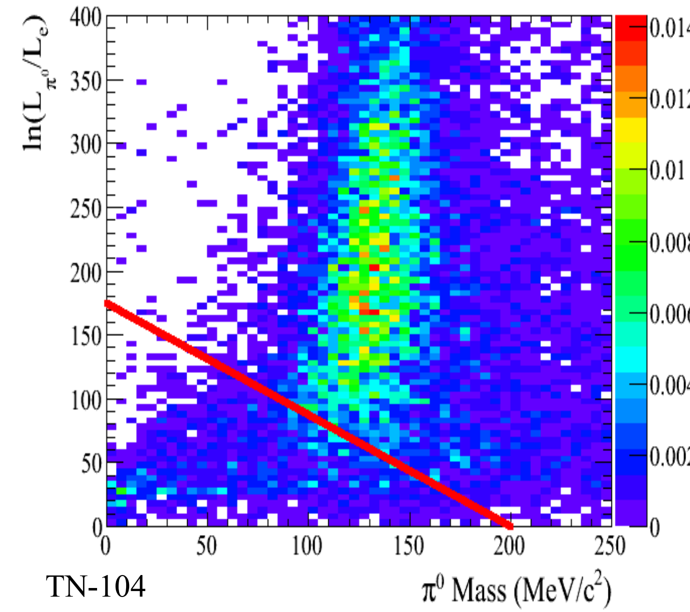
Measurements are combined in a joint fit to constrain the ν fluxes and cross sections

The T2K Far Detector: Super-Kamiokande



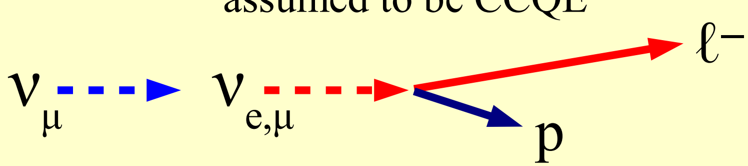
39.3 m

- 50 kt Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
  - Typically 66% ν_e signal eff. (at osc. best fit point)
    - 99.5% π^o rejection
    - 99.98% CC ν_μ rejection
  - 22.5 kt fiducial volume
- Dead-time free DAQ
  - All triggers in ±0.5 ms of neutrino arrival time recorded
- GPS time recorded in real-time for every spill



Signal: Single-ring†

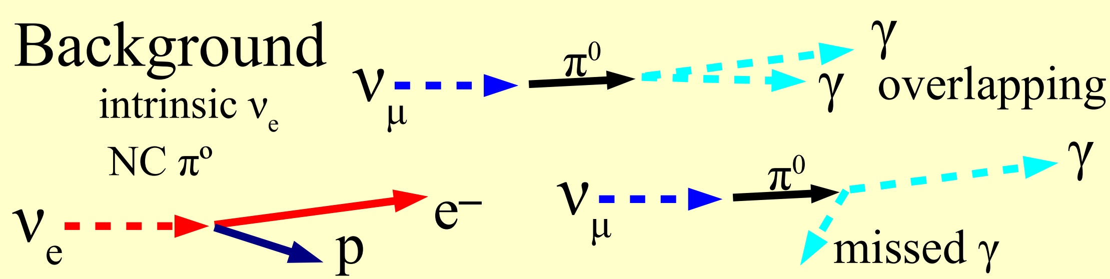
assumed to be CCQE



Background

intrinsic ν_e

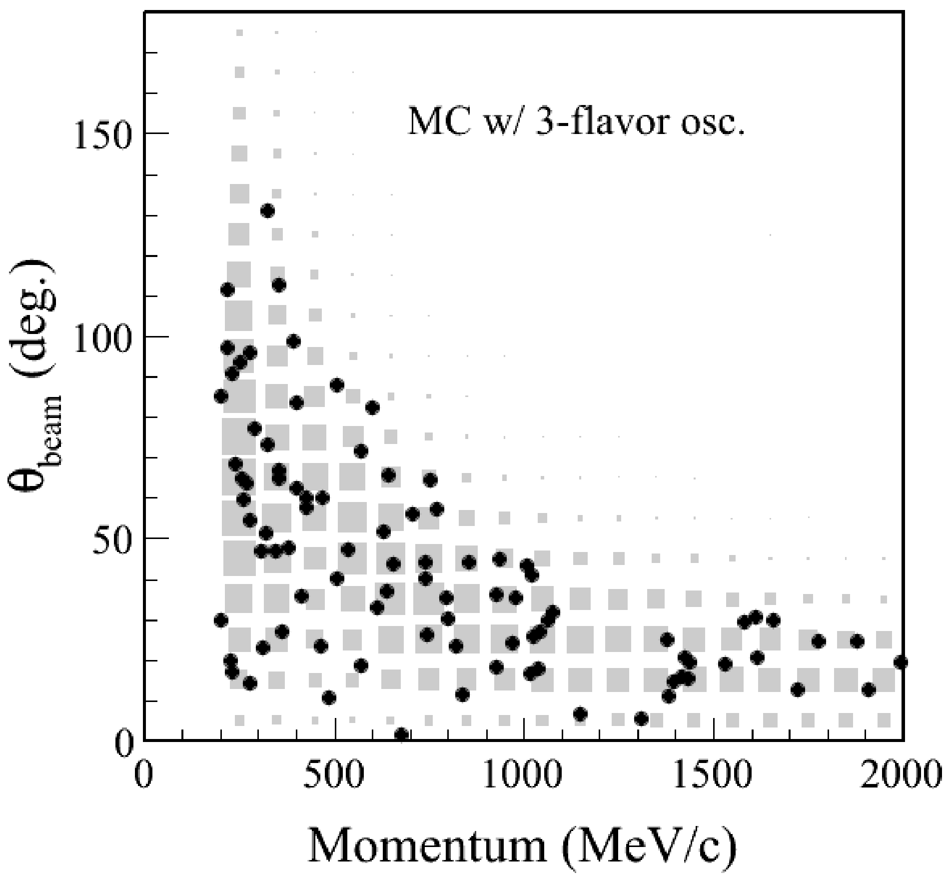
NC π^o



† Anti-neutrinos as well...

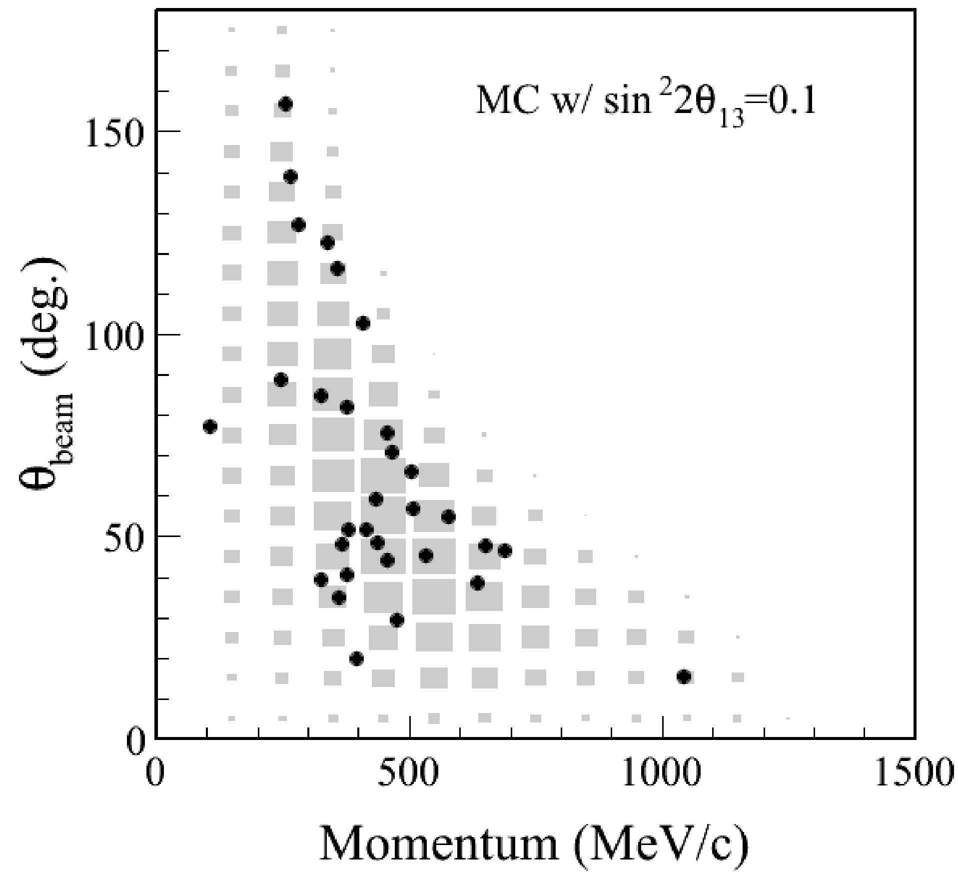
Selected Far Detector Single Ring Event Samples

Selected Single Ring Muon Like



120 candidates

Selected Single Ring Electron Like



28 candidates

T2K-Plots-24

Systematics Summary by Category Without a Near Detector

- Summarizes the effect of 64 error terms on expected number of events
  - Uncertain on other important ratios "tracks" this uncertainty.
  - Effect of correlations treated in the analysis
- Considered to help understand the design of the analysis

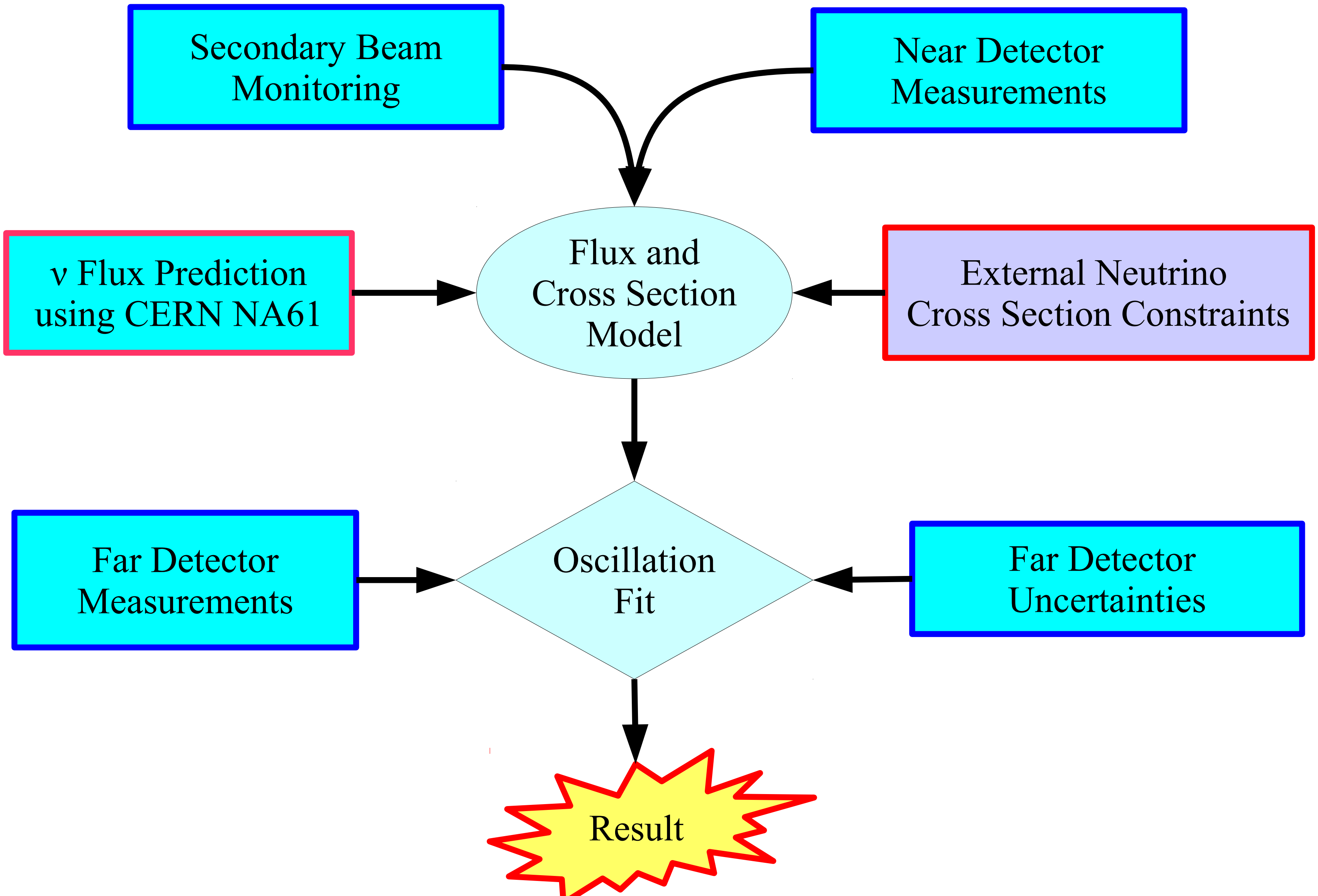
Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK+FSI SK FSI+SI(+PN)	5.00% 4.03% 2.98%	3.66% 2.72% 2.44%
Flux and correlated cross sections (prefit)	$\boxed{21.75\%}$	$\boxed{26.04\%}$
Independent cross sections	5.00%	4.69%
Total (prefit)	23.45%	26.80%

SK Detector Systematics using AtmNu control samples

Final State and Secondary Interaction

X-section uncertainty not currently correlated between near and far detectors.

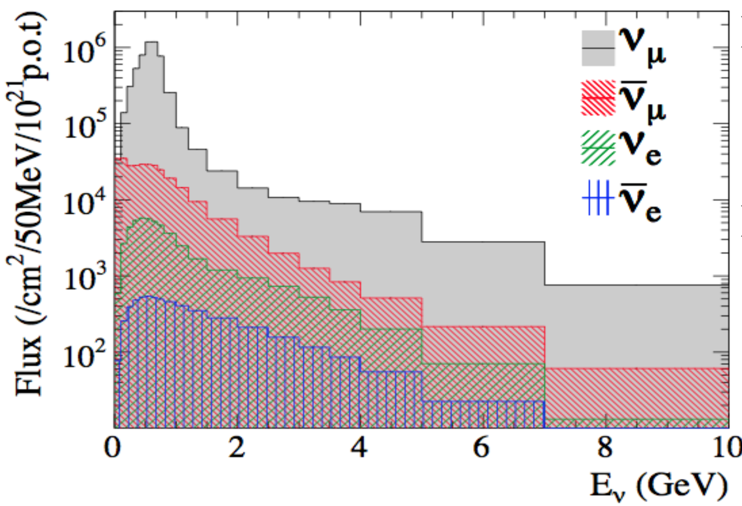
Conceptual Map of the T2K Oscillation Analysis



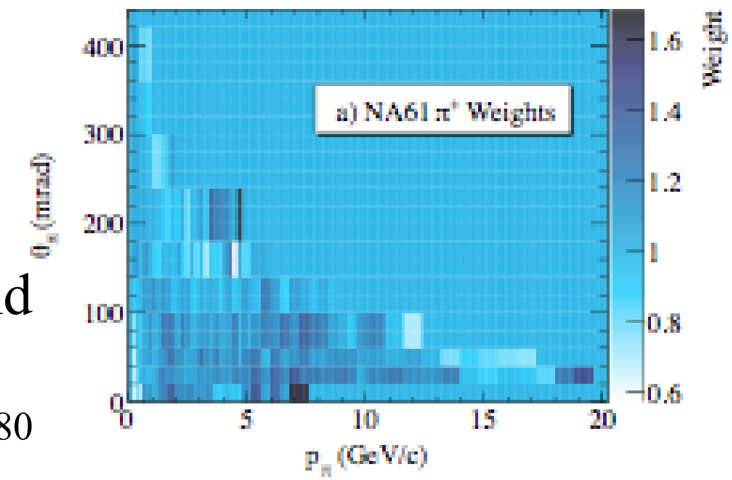
Neutrino Flux Prediction

(using CERN NA61 results)

T2K Run1-4 Flux at Super-K

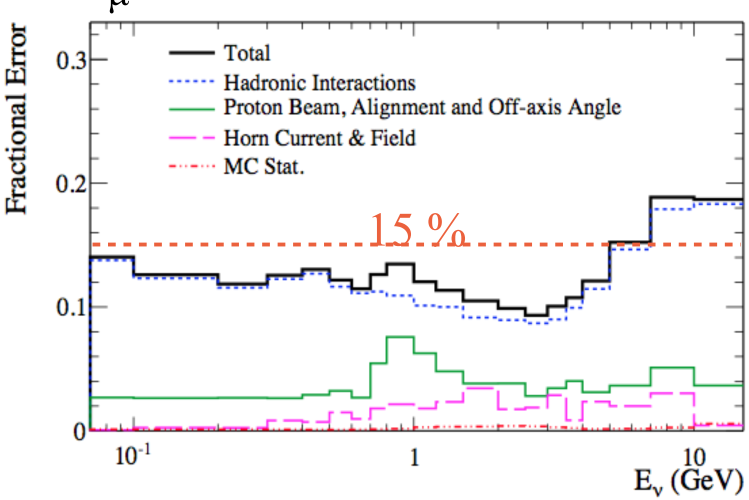


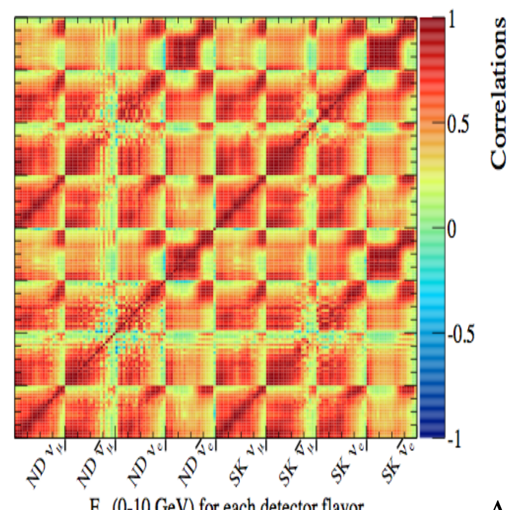
- Hadron production from CERN NA61
  - Both pion and kaon
- Energy dependent errors for ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$
  - Full correlations for ND280 and SK
  - covariance used in flux and cross section fit



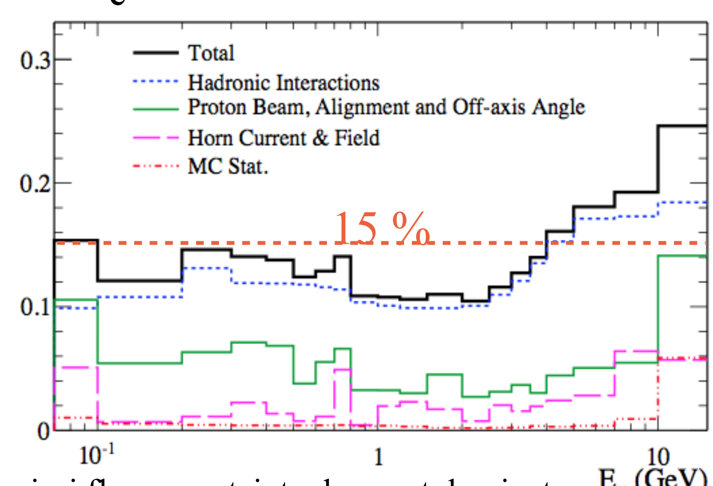
N. Abgrall et al. (NA61/SHINE Collaboration), Phys. Rev. C 84, 034604 (2011)
N. Abgrall et al. (NA61/SHINE Collaboration), Phys. Rev. C 85, 035210 (2012)
T. Eichten et al., Nucl. Phys. B 44 (1972)
J. V. Allaby et al., Tech. Rep. 70-12 (CERN,1970)

ν_μ Flux Uncertainty





ν_e Flux Uncertainty

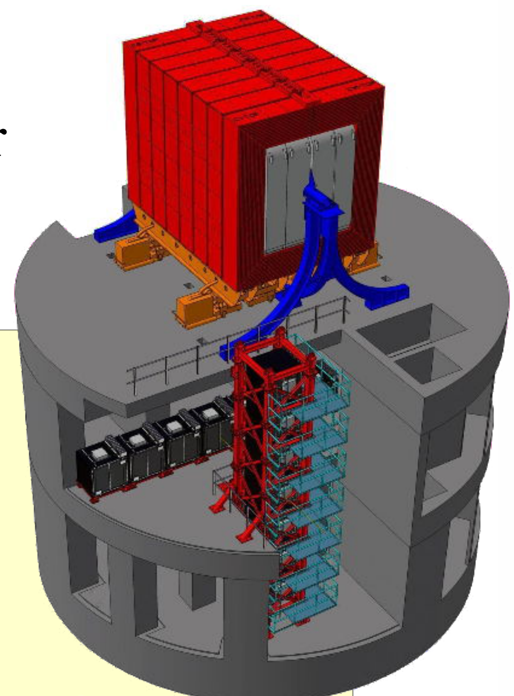


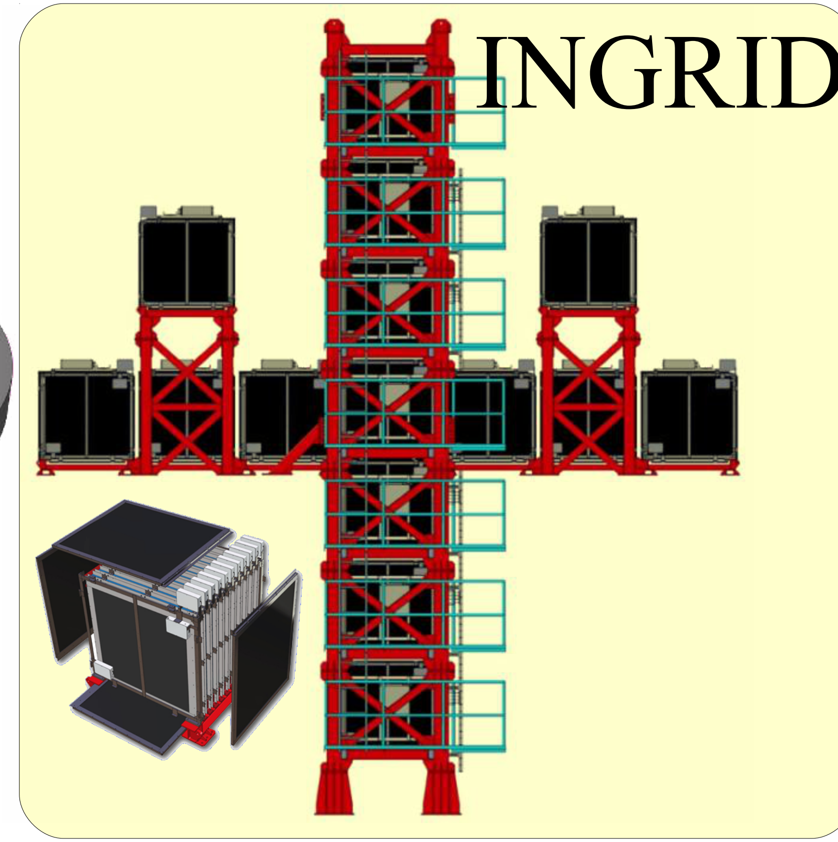
A priori flux uncertainty does not dominate the total N_{sk} uncertainty

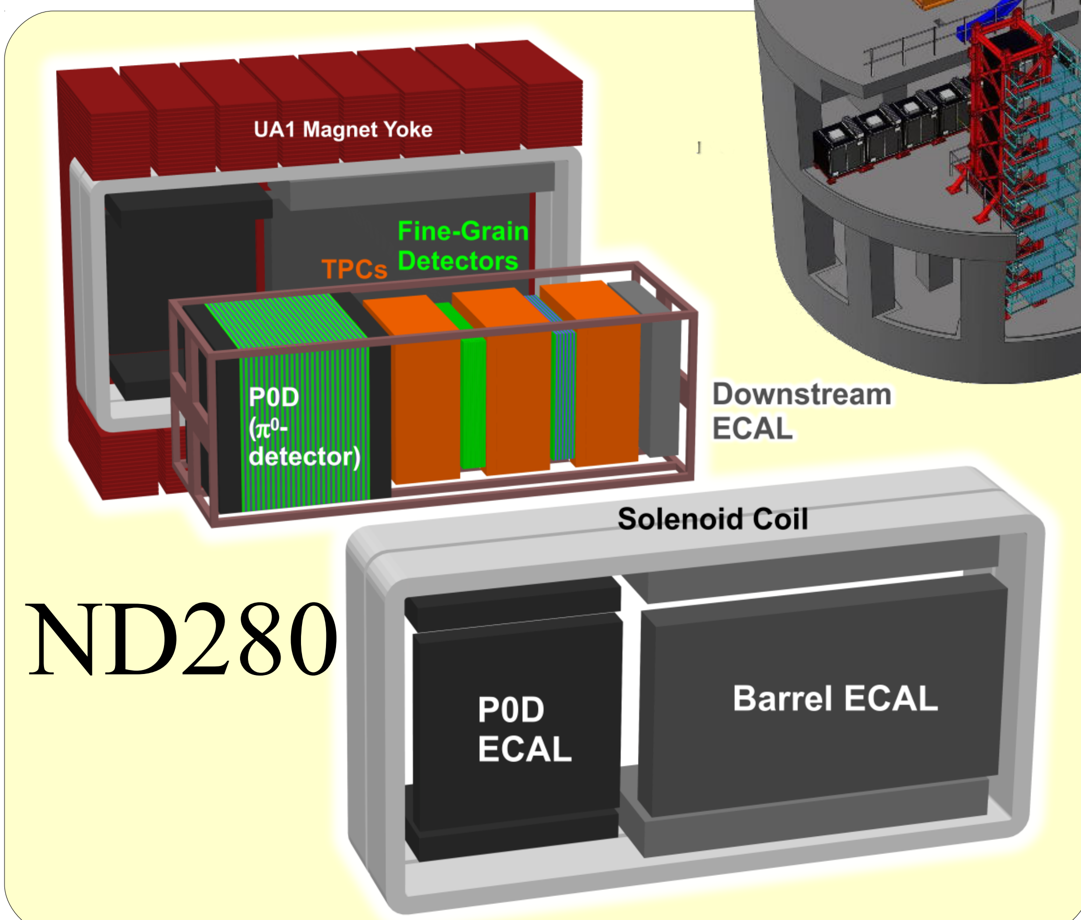
The ND280 Detectors

(Near Detectors @ 280 Meters)

- On-Axis: INGRID
  - Neutrino Beam Monitor
    - Direction
    - Rate

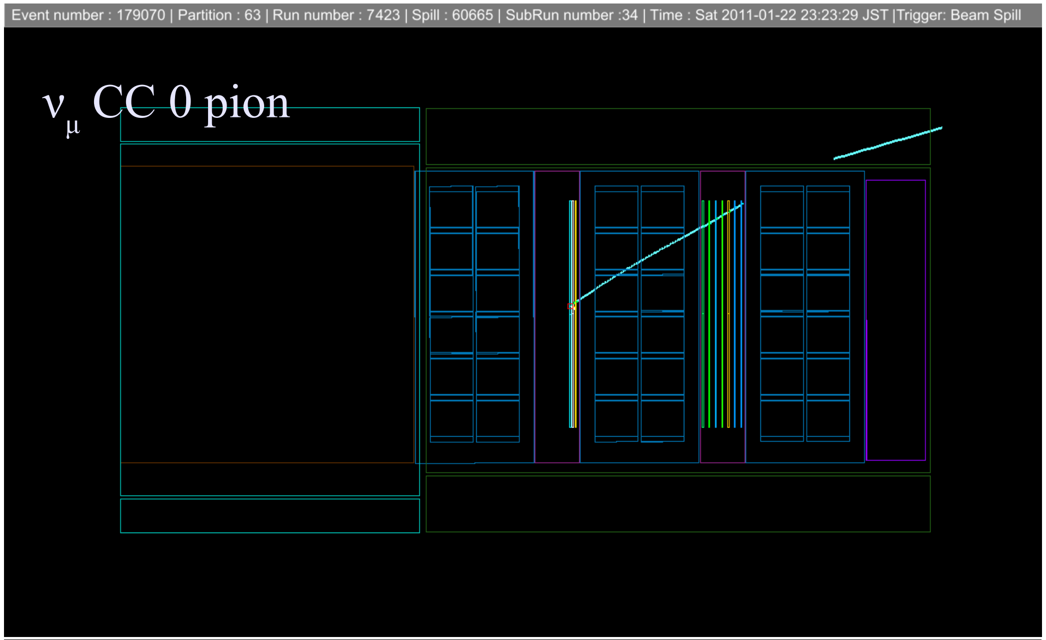


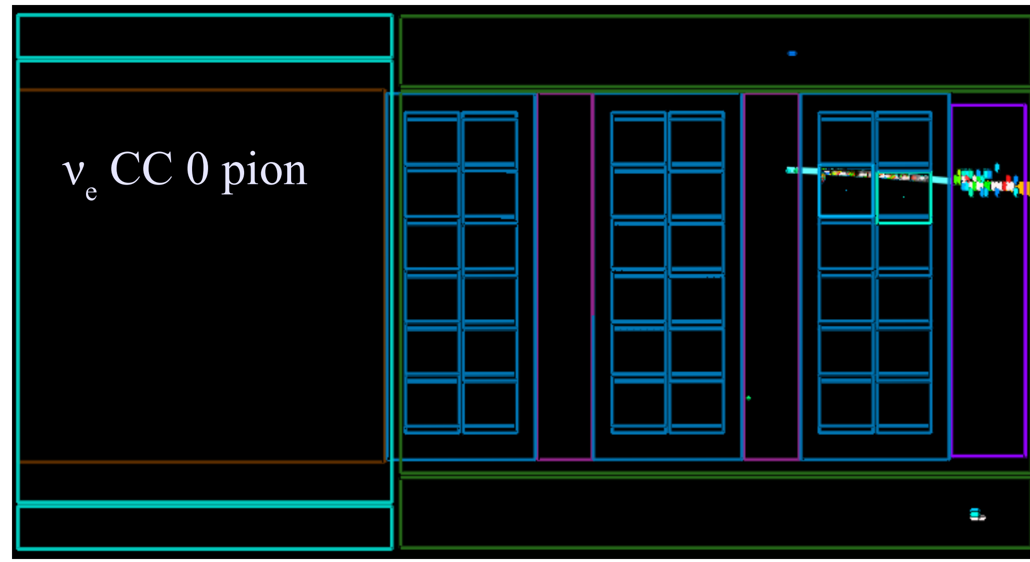


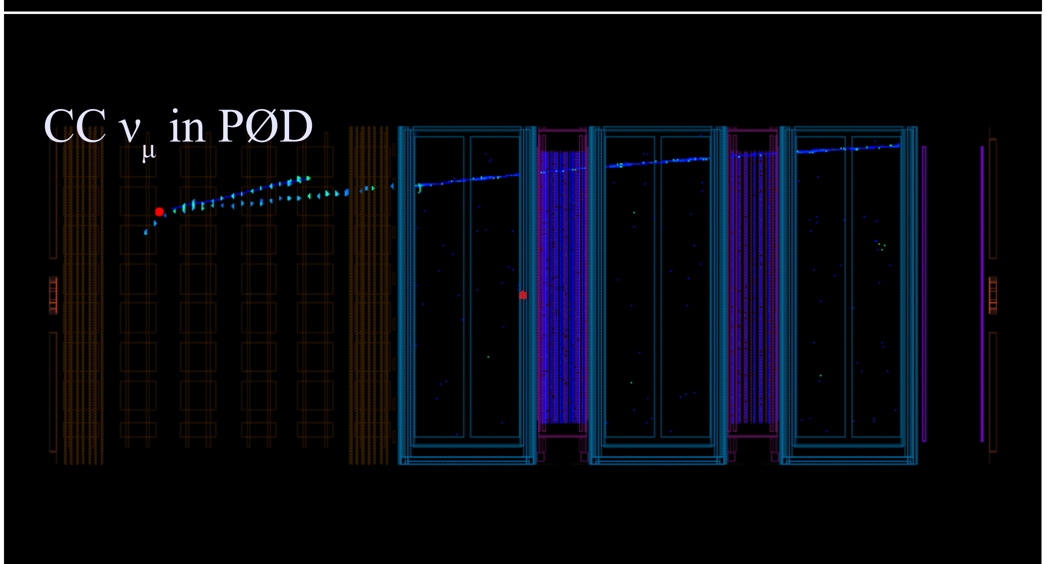


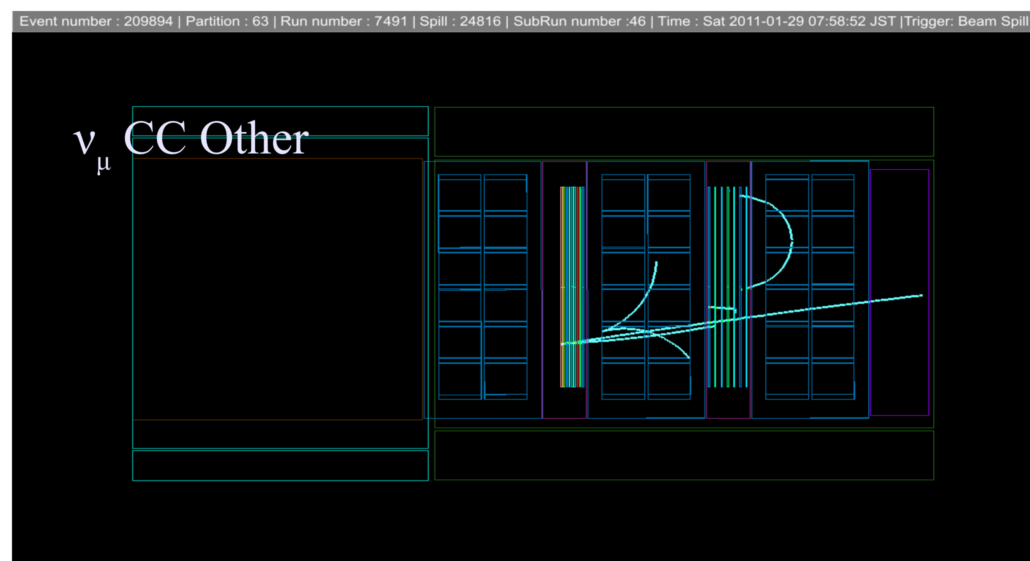
- Off-Axis: ND280 @ 2.5 deg
  - Off-axis flux and cross-sections
  - Target with water for stat. subtraction
  - In UA1/NOMAD magnet (0.2 T)
    - Target+Particle Tracking
    - π^o detection
    - EM calorimetry
    - Side muon range detection

Typical ND280 Events



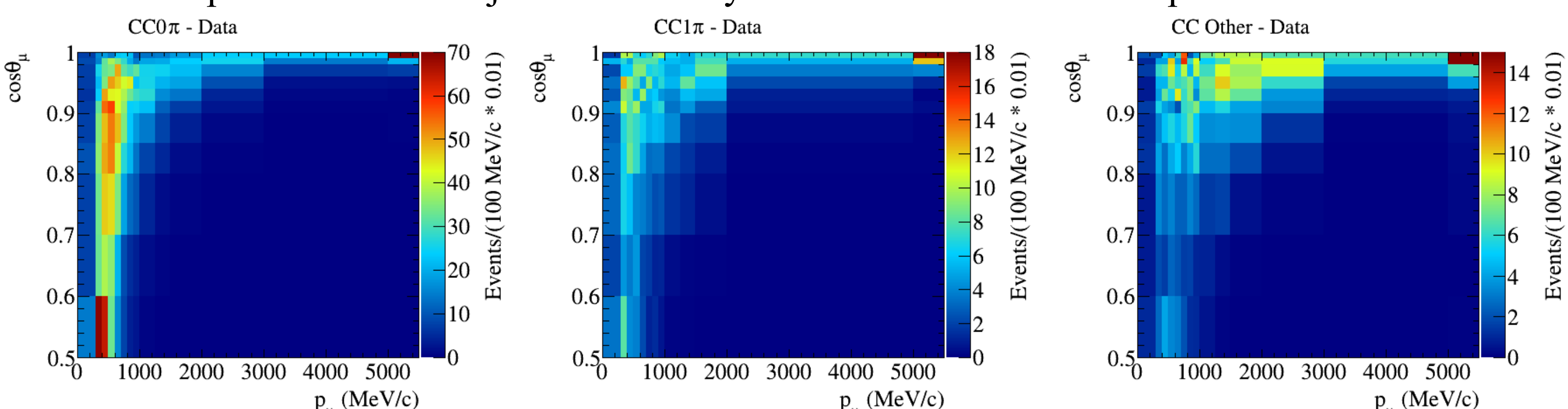






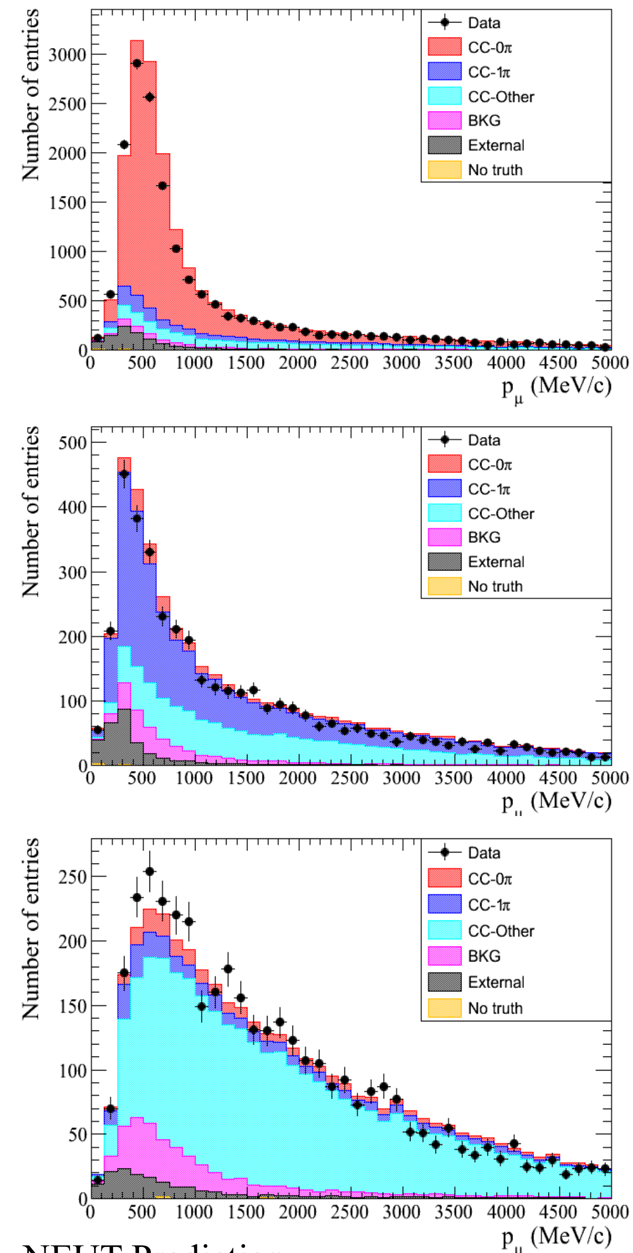
CC Muon Neutrino Samples

- FGD 1 (scintillator only) Muon neutrino CC inclusive sample
  - Data quality (including a reconstructed TPC track)
  - Highest momentum track in TPC is muon like
    - Sample has a 91% purity and a 25% efficiency
  - Target with water (FGD2) not currently in the analysis
- Sub-Samples of the inclusive selection
  - CC zero pion sample
    - No $\pi^{\pm}$ in TPC, no $e^{\pm}$ in TPC, no Michel-e in FGD, no π in FGD
  - CC one pion sample
    - Has π^{+} signature, No π^{-} in TPC, no $e^{\pm}$ in TPC
  - Other inclusive events
    - The rest of the inclusive sample
- Sub-samples are used in a joint fit of all systematic and cross-section parameters



Composition of the ν_μ Samples

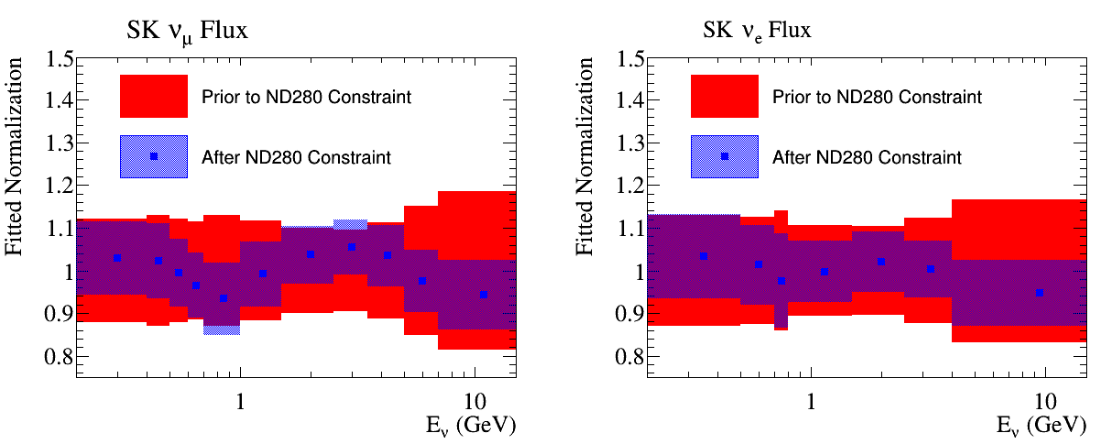
- Samples chosen to select events based on event topology
  - Less sensitivity to specific neutrino models
  - Better separation between detector and model uncertainties
- None of the samples are "pure", but the combination provides good constraint on the mixture of final states.
- Shape and normalization provide constraints on the flux and cross section



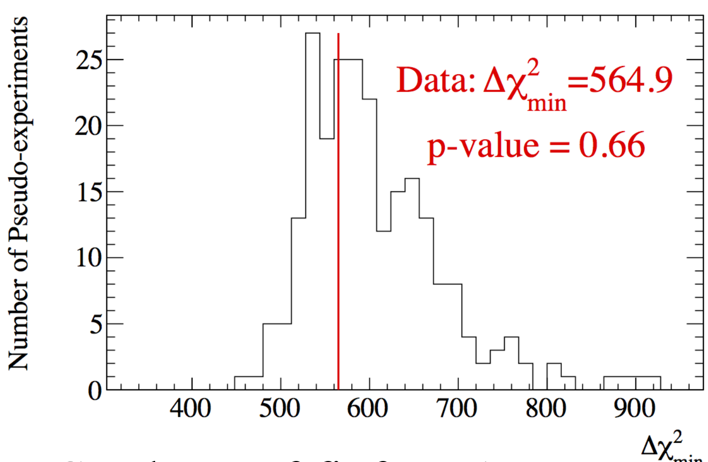
NEUT Prediction

Fit to ND280 CC ν_μ Constraints

- ND280 Near Detector Data constrains flux and cross section parameters used in the oscillation fit
  - Two approaches have been used
    - Fit ND280 data and provide a covariance matrix for later use.
      - 33 output parameters, ~70 nuisance parameters to describe systematic errors
    - Joint fit to ND280 and SK data (using MCMC to handle large number of parameters)
      - MCMC also fits just ND280 so approaches are cross-validated.
  - Apply external constraints based on prior measurements
- More ND280 measurements will be incorporated in the future
  - e.g. CC ν_μ on water. CC ν_e, NC π^o, anti-neutrino data



Similar reductions in the cross section uncertainty



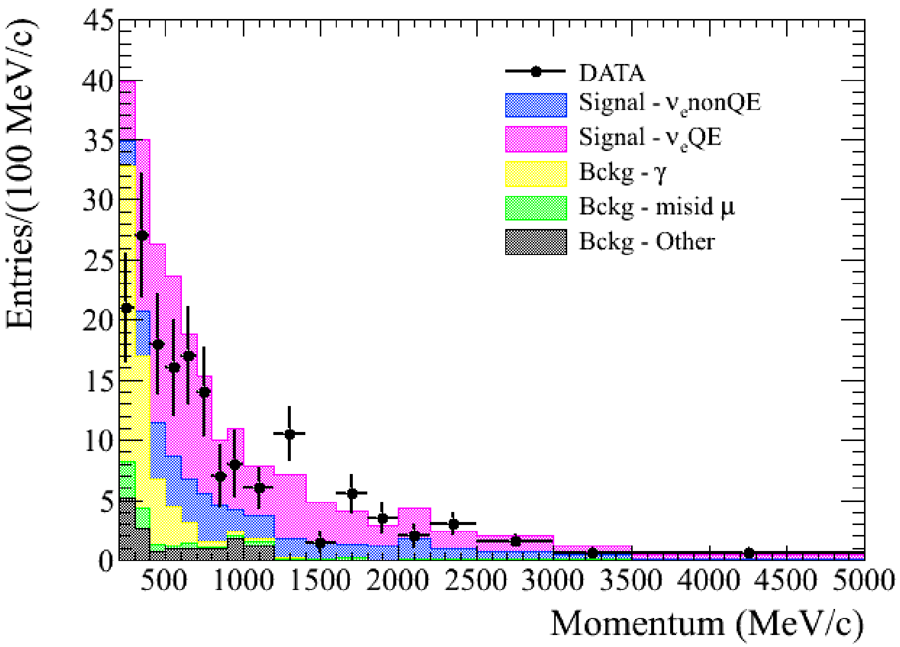
Goodness-of-fit for BANFF

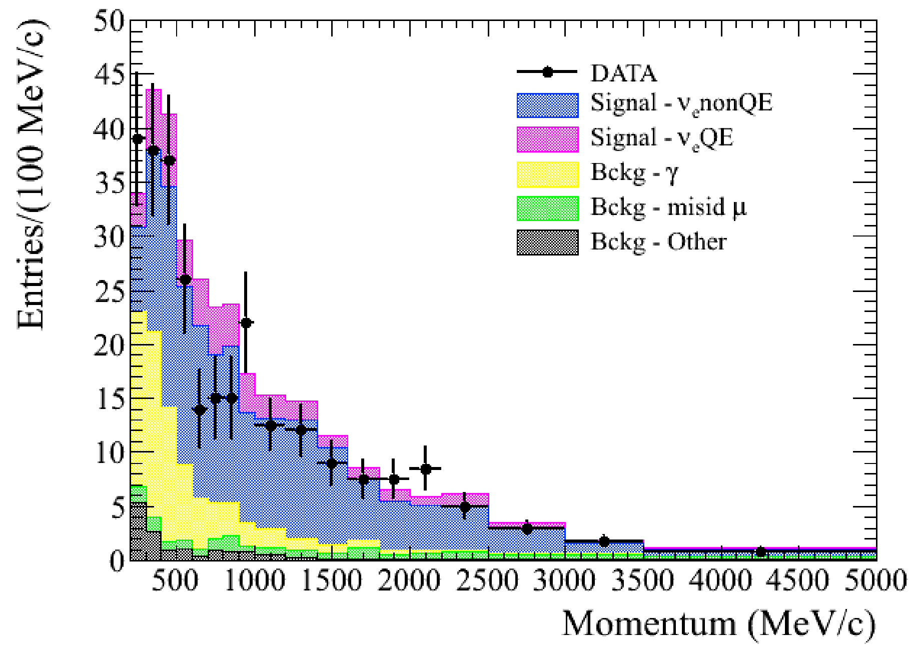
Non CC ν_μ Constraints

- All of the neutrino (largely) come from the same beam line physics, so measurements of CC $\nu\mu$ interactions provide constraints on other neutrino flavors.
  - Direct constraint is better
- For electron neutrino appearance, two interactions can fake the oscillation signal
  - Intrinsic beam ν_e
  - Misidentified NC π^o production

Near Detector ν_e Measurement

- Provides check of the intrinsic ν_e content of the T2K neutrino beam.
- Fit results
  - Data/MC for ν_e CCQE: 1.10 ± 0.14 (stat) ± 0.10 (sys)
    - Purity is 48% (67% of events are from ν_e)
  - Data/MC for ν_e non-CCQE: 1.03 ± 0.11 (stat) ± 0.12 (sys)
    - Purity is 53% (66% of events are from ν_e)

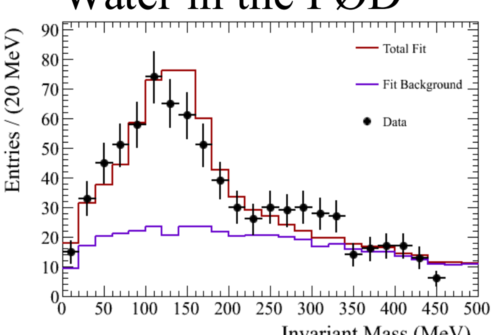




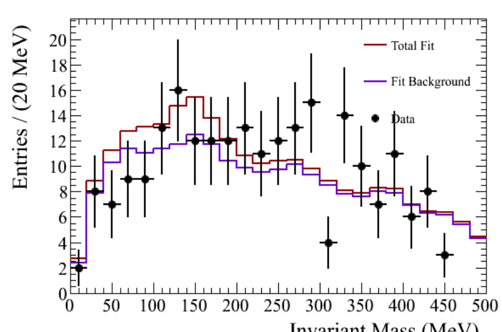
Check of NC π^o Rate

- Signal defined as
  - One π^o leaving the target nucleus
  - No charged lepton or charge pion
  - Any number neutrons or protons leaving the target nucleus.
- Fit to the observed π^o invariant mass peak
  - Constrain background using signal side-bands
    - Invariant mass and muon decay tagged sidebands.
- The ND280 detector was designed to measure cross sections on water using statistical subtraction
  - Water In Measurement: 0.944 ± 0.076 (stat) ± 0.231 (sys)
  - Water Out Measurement: 1.107 ± 0.101 (stat) ± 0.316 (sys)
  - Subtracted Measurement: 0.652 ± 0.270 (stat) ± 0.576 (sys)
- Source of systematics has been identified and targeted for reduction

Water in the PØD

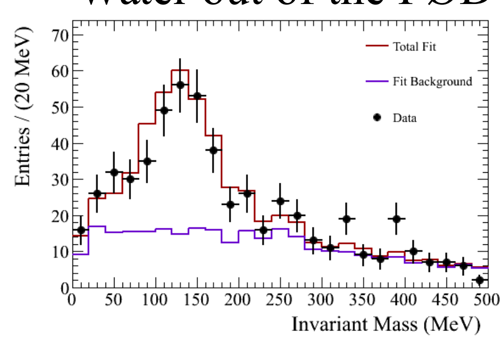


Signal Band

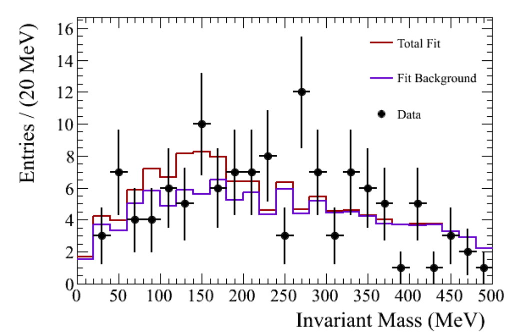


μ-dk Band

Water out of the PØD



Signal Band



μ-dk Band

Systematic Error Summary After Near Detector Constraints

- Summarizes the effect of 64 error terms in the joint fit on expected number of events
  - Uncertain on other important ratios "tracks" this uncertainty.
  - Effect of correlations treated in the analysis

Source of uncertainty	1Rμ $\delta N_{SK}/N_{SK}$	1Re $\delta N_{SK}/N_{SK}$
SK+FSI SK FSI+SI(+PN)	5.00% 4.03% 2.98%	3.66% 2.72% 2.44%
Flux and correlated cross sections (prefit) (postfit)	 21.75% 2.74%	 26.04% 3.15%
Independent cross sections	5.00%	4.69%
Total (prefit) (postfit)	 23.45% 7.65%	 26.80% 6.75%

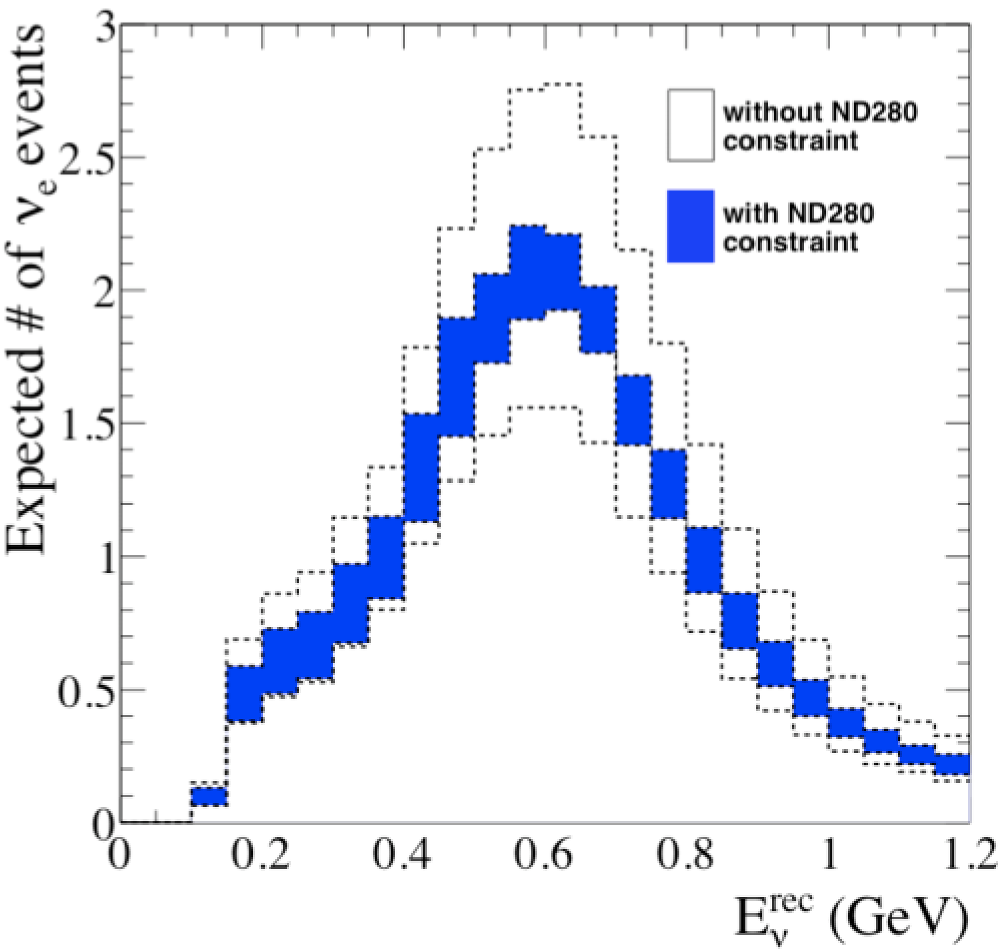
New tools are being developed to reduce SK uncertainties

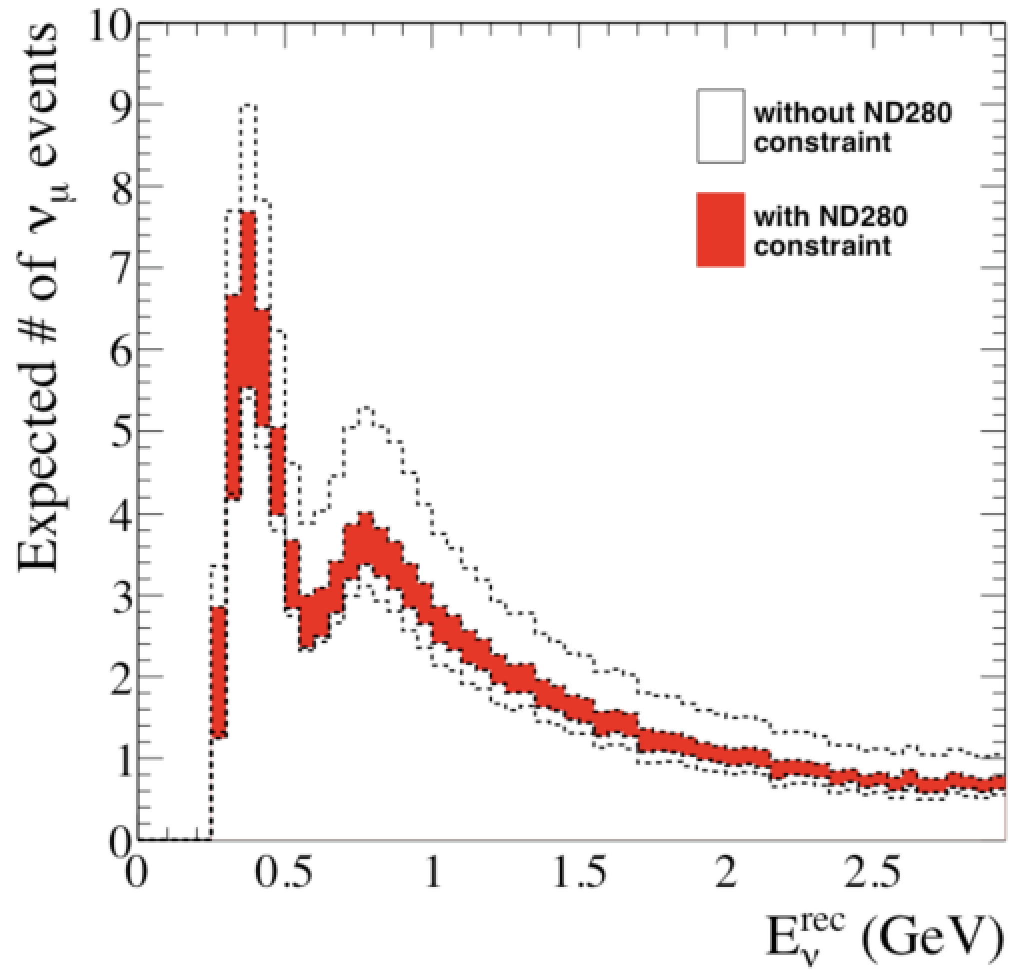
Will be reduced as we add more ND samples

Joint Fit to ν_μ and ν_e Oscillations

- T2K has moved from establishing non-zero ν_e into precision measurements of the oscillation parameters.
  - Simultaneous fit to all oscillation parameters.
  - The first joint fit uses the single ring muon and electron like samples.
    - Important observables are:
      - Ring type (electron or muon like)
      - Ring direction (relative to the beam direction)
      - Ring momentum (depends on the ring type)
    - Three fits done as an internal cross check (with quite different approaches)
      - Two use the observables to reconstruct and fit the apparent neutrino energy
      - One directly fits the angle relative to the beam and the particle momentum
      - Two produce regions using $\Delta\mathcal{L}$ (both fixed and FC), one produces credible regions
      - One fit uses an MCMC to map a posterior
      - Two use a downhill gradient descent
    - All three fits use the same systematic error inputs, but different internal handling

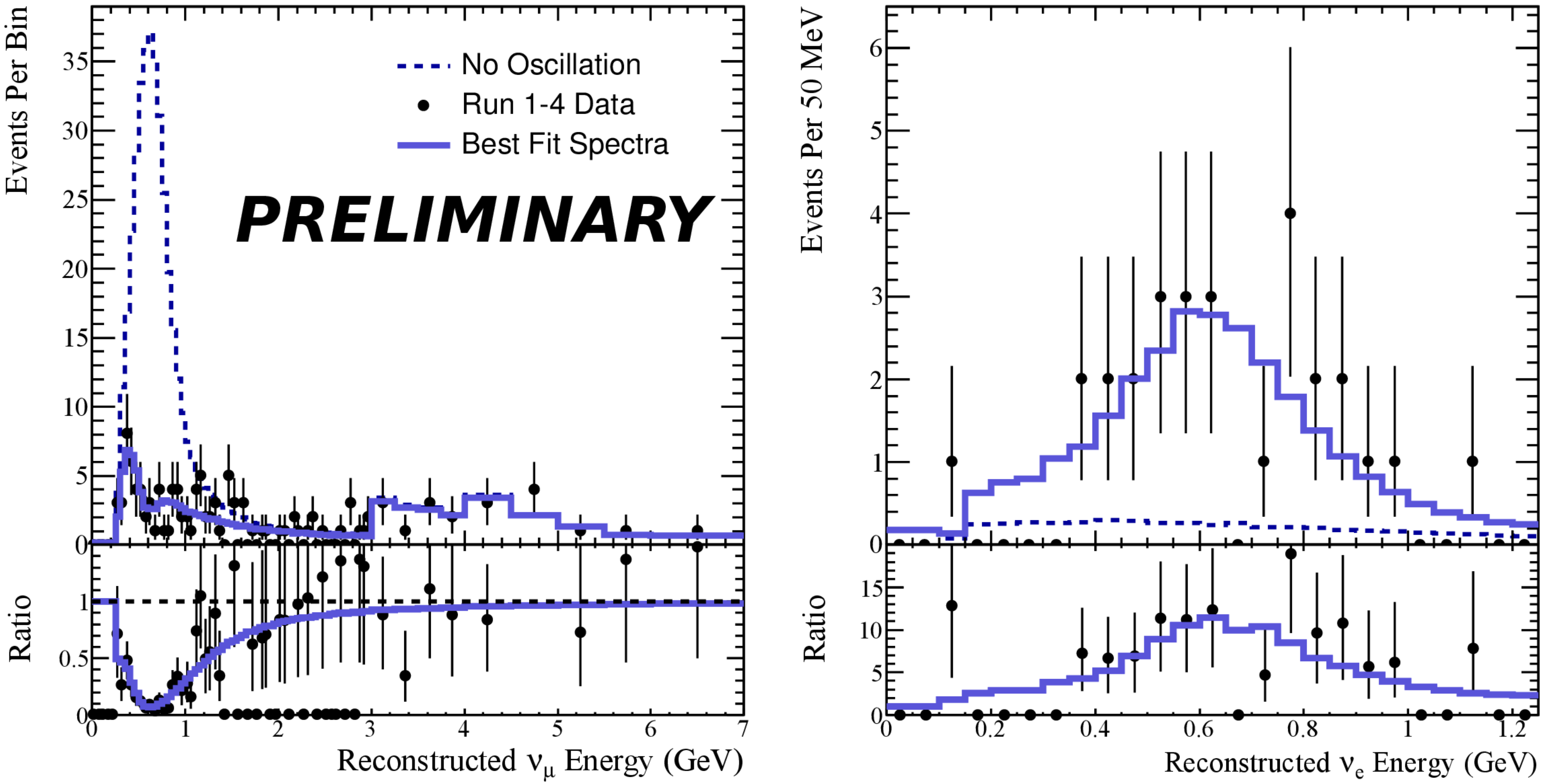
Reconstructed Neutrino Energy After Near Detector Constraints





Expected reconstructed neutrino spectra near joint oscillation best fit point
This includes the effects of both flux and cross section uncertainty

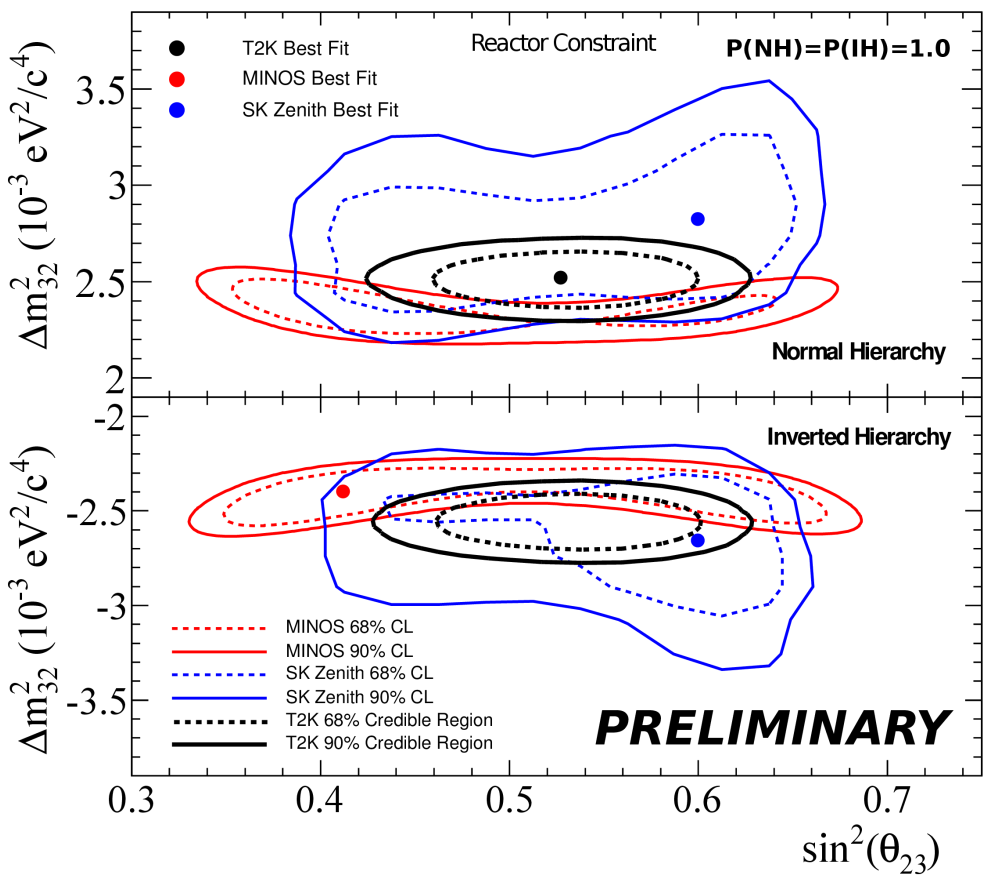
The T2K Joint ν_μ & ν_e Fit Result

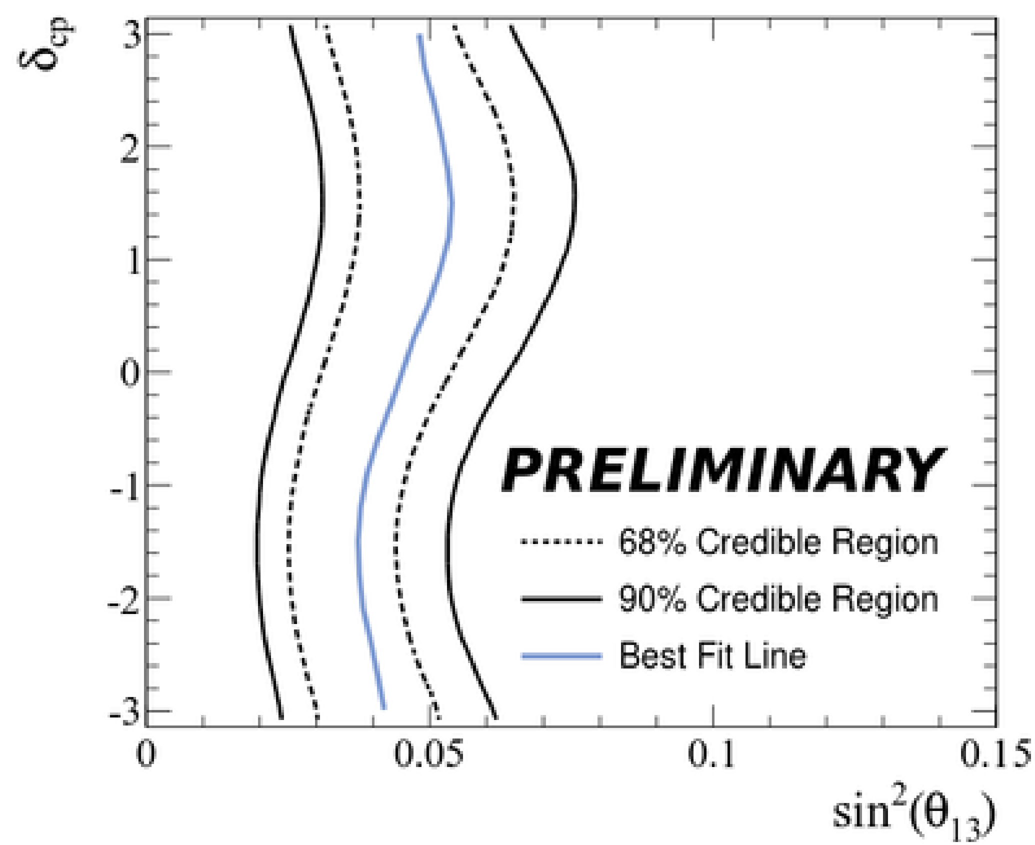


Best Fit: $\Delta m^2_{32} = -2.57 \pm 0.11 \times 10^{-3}\ \mathrm{eV}^2$; $\sin^2\theta_{32} = 0.520^{+0.045}_{-0.050}$ $\sin^2\theta_{13} = 0.0454^{+0.011}_{-0.014}$

T2K-Plot-28 (Mach3)

Combined ν_μ & ν_e Oscillation Fit





Conclusions and Summary

- Understanding neutrino cross section physics is going to play a large role in the ability to make precision oscillation measurements.
- The T2K ND280 detectors are a powerful tool for reducing systematic uncertainty in oscillation analysis.
  - e.g. Number of single ring muon events: 23.45% → 7.65%
  - Beginning to incorporate more samples to provide more constraint on neutrino flux and cross section
- T2K is still in the early days of it's program
  - Expecting data sample to increase by more than an order of magnitude.

The T2K Collaboration

Canada

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U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
U.Winnipeg
York U.

France

CEA Saclay
IPN Lyon
LLR E. Poly
LPNHE Paris

Germany

Aachen U.

Italy

INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

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KEK
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Kyoto U.
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Osaka City U.
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NCBJ, Warsaw
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Switzerland

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U. Geneva

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U. Sheffield
STFC/RAL
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U. Warwick

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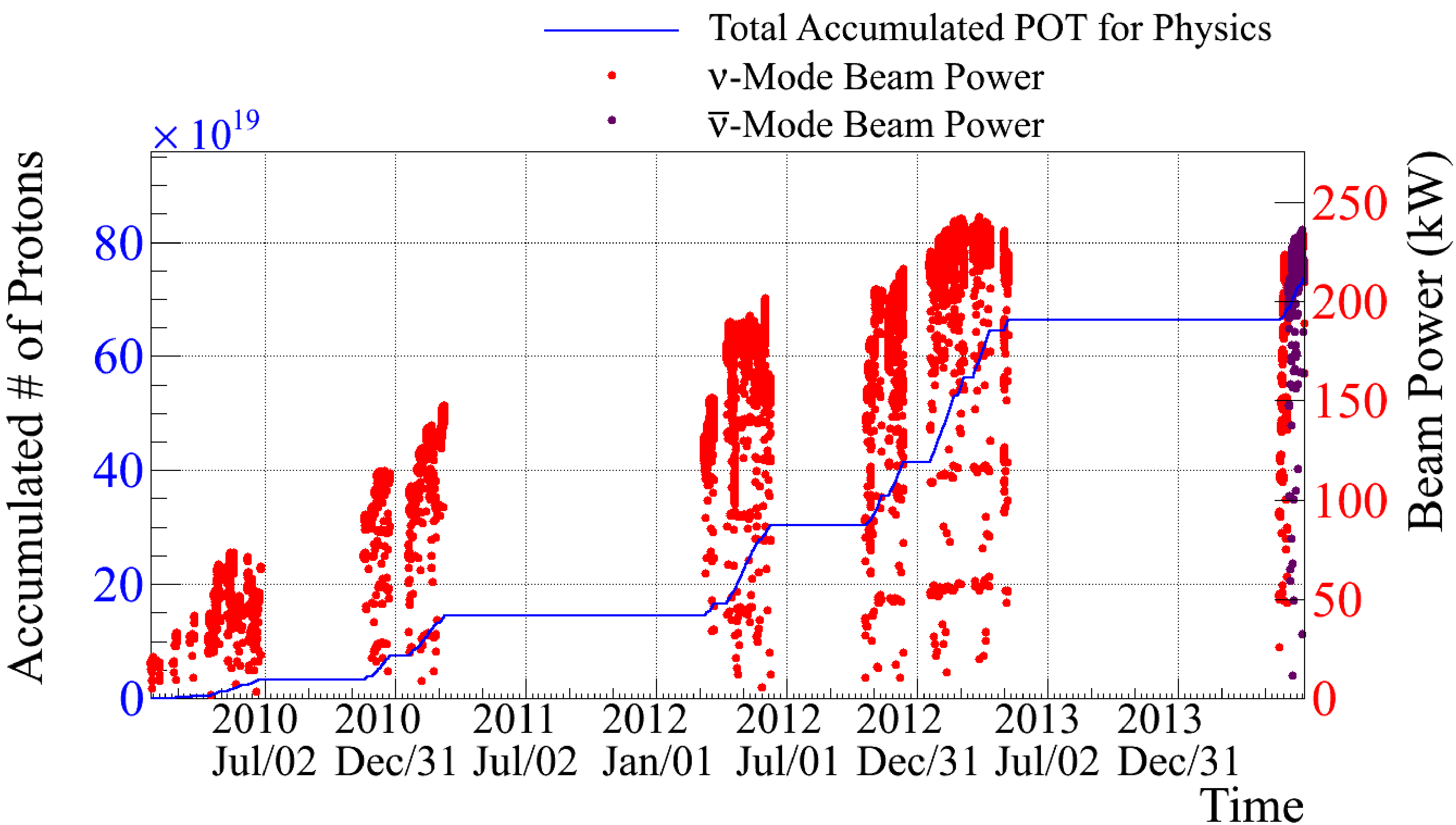
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Host Institutions: KEK (J-PARC), ICRR (Kamioka Observatory)

11	Countries
56	Institutions
~340	Authors

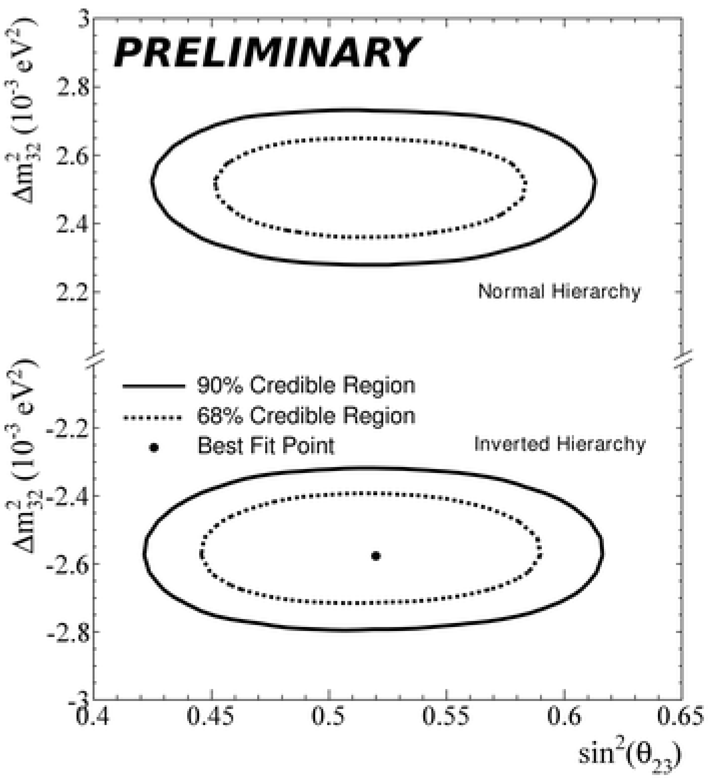
Backup Slides

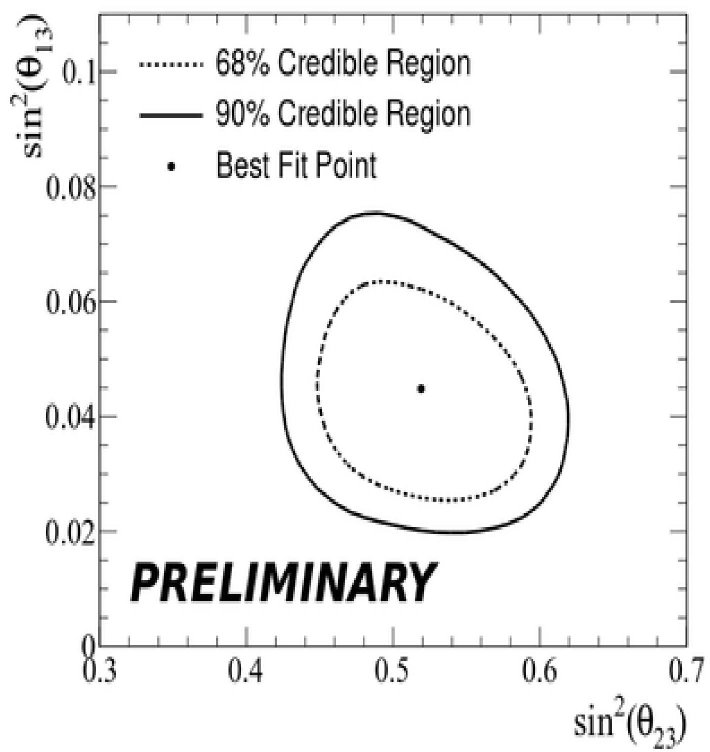
T2K Accumulated Protons on Target



Neutrino mode: 6.57×10^{20} protons on target (8% of expected)

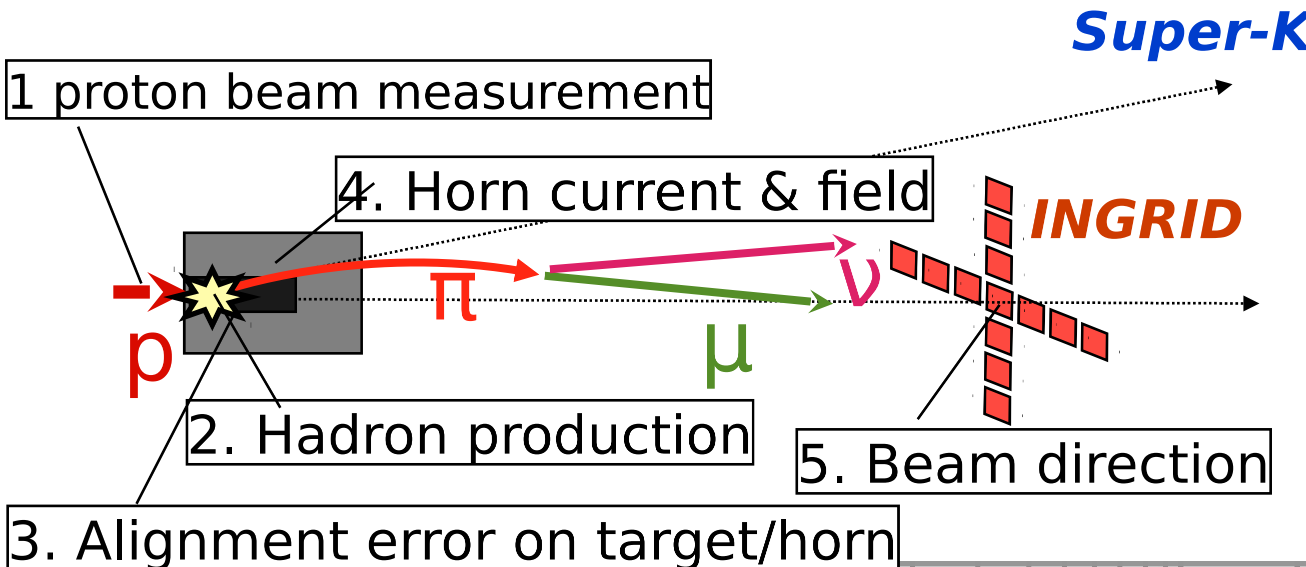
The T2K Joint ν_μ & ν_e Oscillation Fit



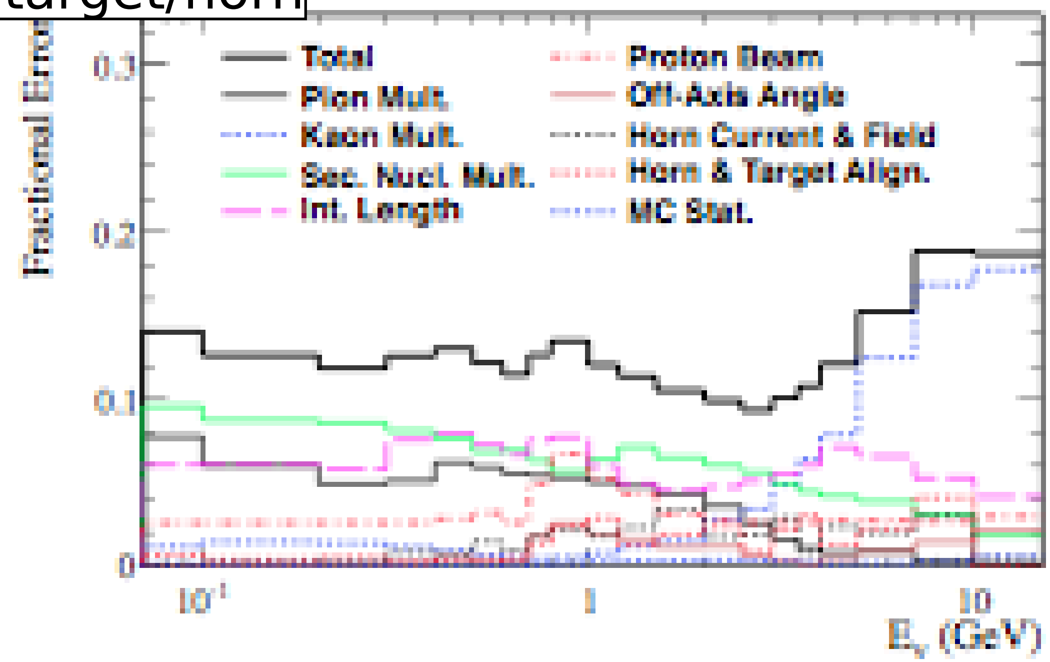


Credible regions: All oscillation parameters are fitted, including δ_{cp} and mass hierarchy. Priors are uniform in the plotted parameter.

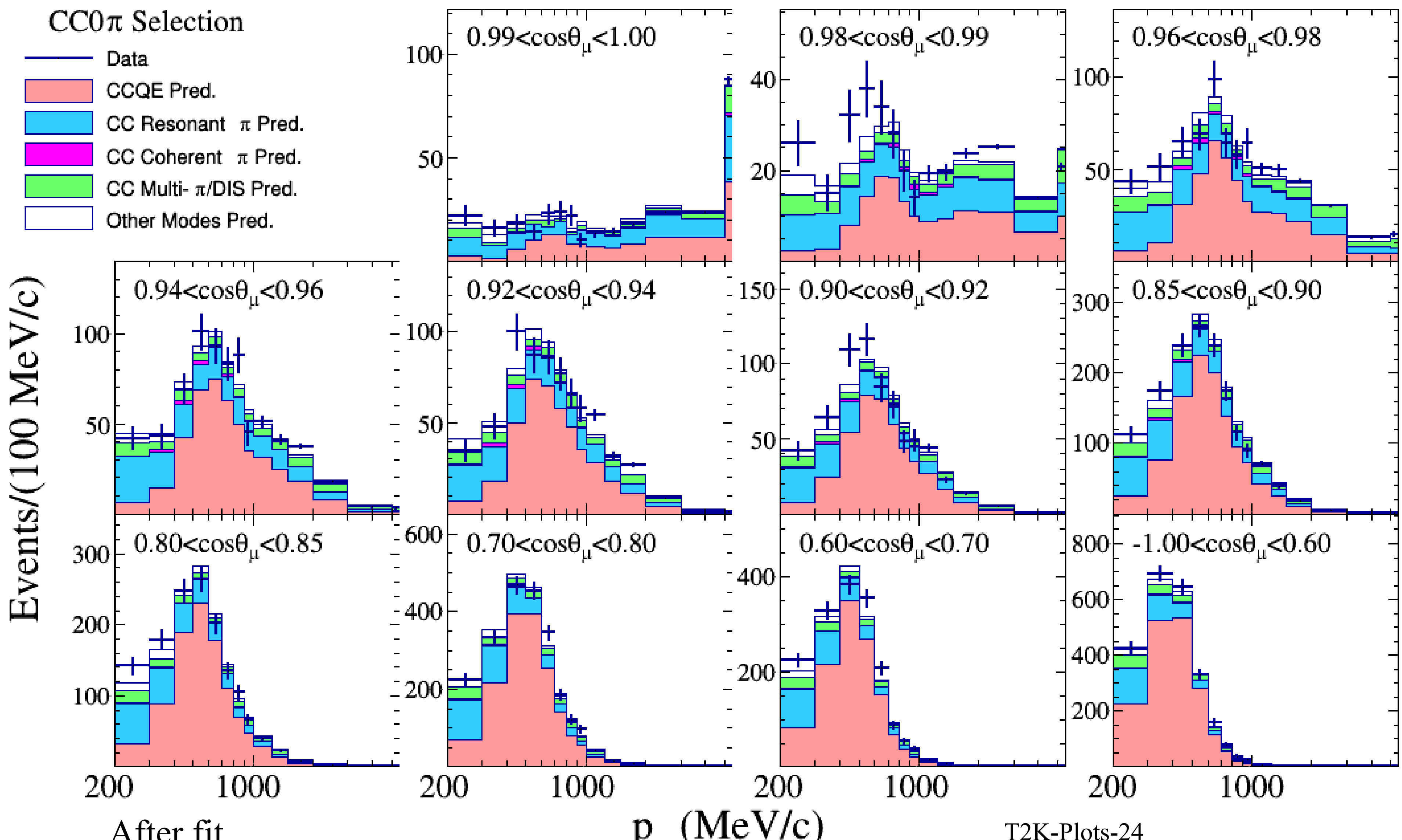
Flux Systematic Error Sources



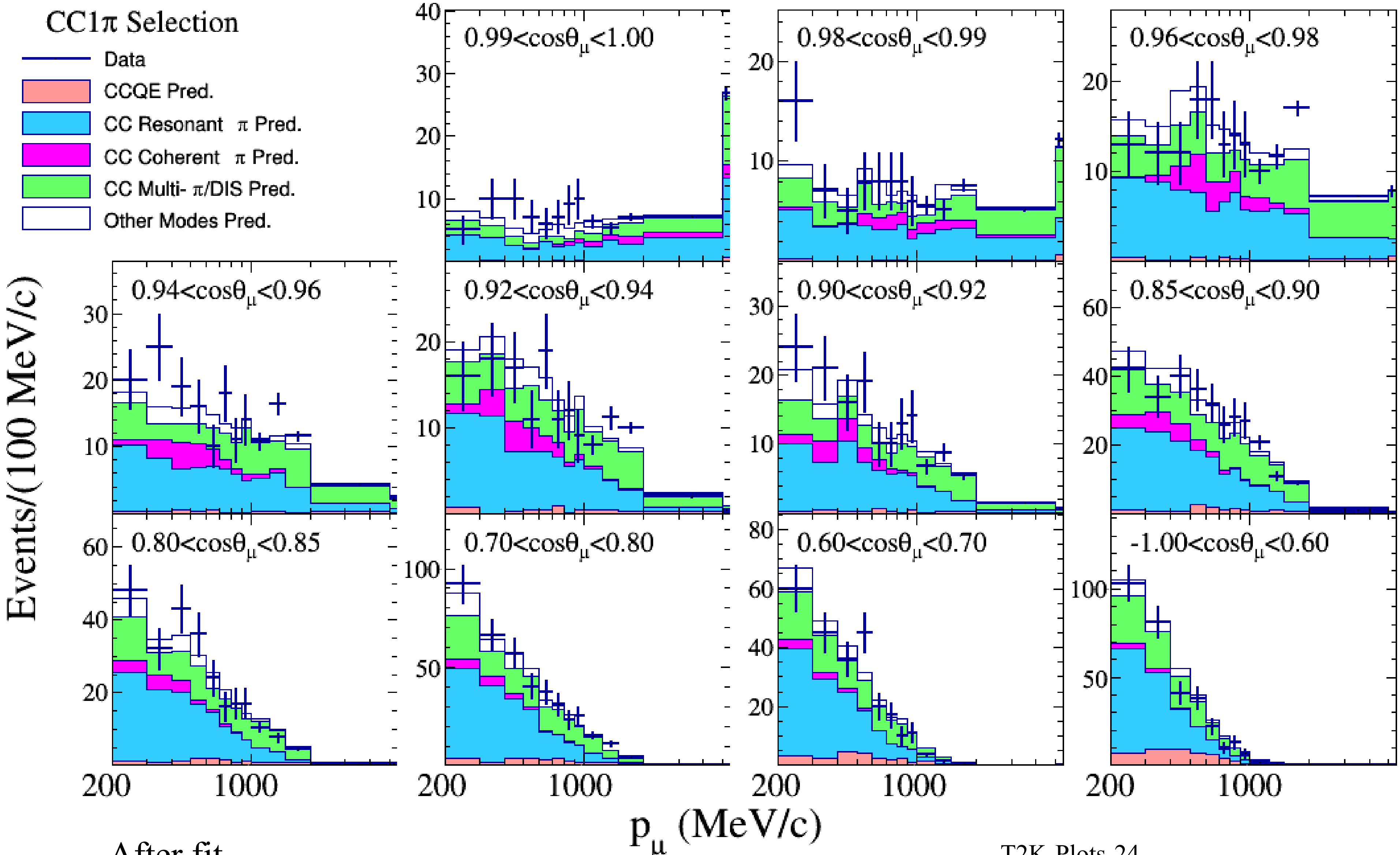
1) Measurement error on monitoring proton beam
2) Hadron production
3) Alignment error on the target and the horn
4) Horn current & field
5) Neutrino beam direction (Off-axis angle)



CC Zero Pion Selection



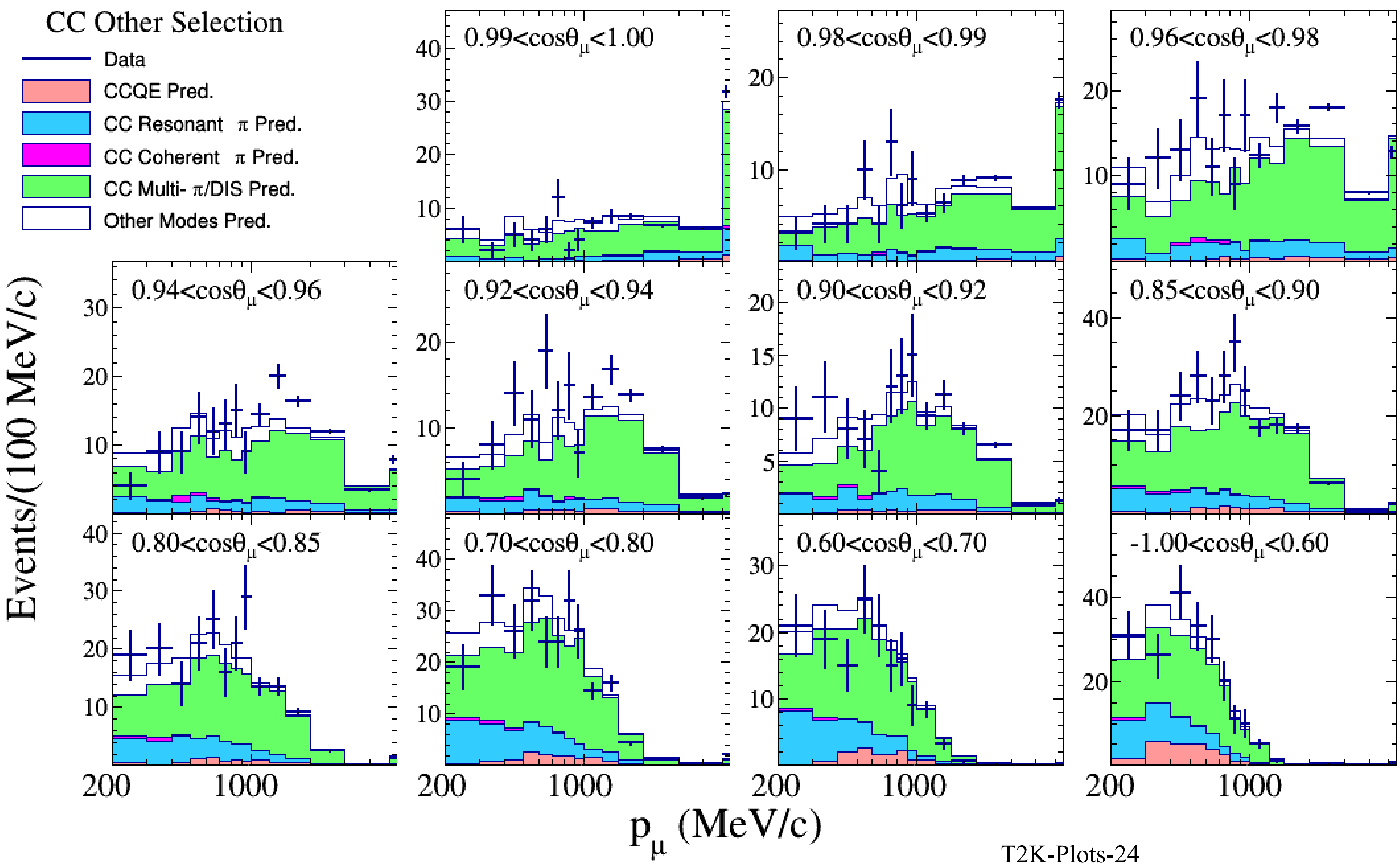
CC One Pion Selection



After fit

T2K-Plots-24

CC Not Zero or One Pion Selection



T2K-Plots-24

Electron Like Sample Details

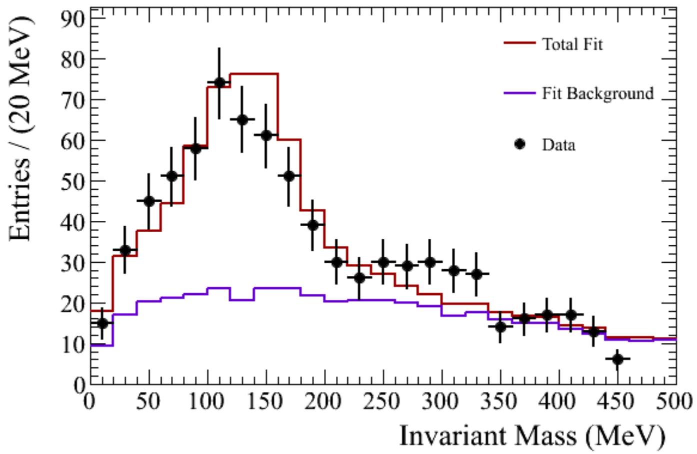
RUN1-4 6.570×10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}=0.1$					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
True FV	325.67	15.97	288.11	629.75	27.07	-
FCFV	247.75	15.36	83.02	346.13	26.22	377
One-ring	142.44	9.82	23.46	175.72	22.72	193
e-like	5.63	9.74	16.35	31.72	22.45	60
E_{vis}>100MeV	3.66	9.68	13.99	27.32	22.04	57
No decay-e	0.69	7.87	11.84	20.40	19.63	44
E_ν^{rec}<1250MeV	0.21	3.73	8.99	12.94	18.82	39
fiTQun π^0	0.07	3.24	0.96	4.27	17.32	28
Efficiency [%]	0.0	20.3	0.3	0.7	64.0	-

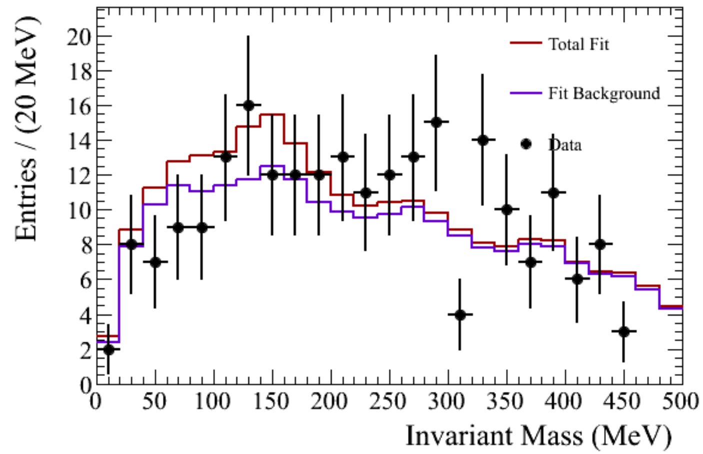
Muon Like Sample Details

RUN1+2+3+4 6.393x10[20]POT	Data	MC Expectations w/ $\sin^2 2\theta_{13}=0.1$				
		MC total	ν_μ+antiν_μ CCQE	ν_μ+antiν_μ CC non-QE	ν_e+antiν_e CC	NC
Interactions in FV	549	656.83	111.71	213.96	43.05	288.11
FCFV	377	372.35	85.55	162.2	41.58	83.02
Single-ring	193	198.44	80.57	61.87	32.54	23.46
μ-like PID	133	144.28	79.01	57.8	0.35	7.11
p_μ>200MeV/c	133	143.99	78.84	57.77	0.35	7.04
N_{dcy-e}<=1	120	125.85	77.93	40.78	0.35	6.78
Efficiency [%]	-	19.2	69.8	19.1	0.8	2.4

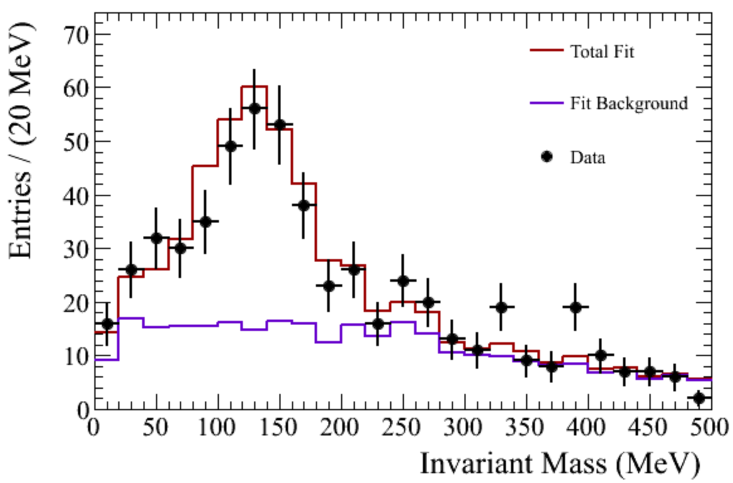
Reconstructed π^o Invariant Mass

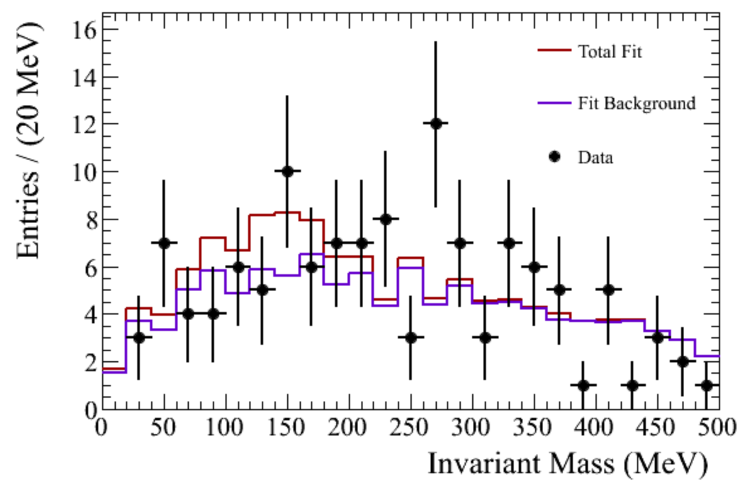
Water in the PØD





Water out of the PØD





Reconstructed π^o energy distribution